



Lawrence Berkeley Laboratory
CENTER FOR BEAM PHYSICS

Lasers in Particle and Beam Physics

by
Swapan Chattopadhyay

SLAC
Colloquium

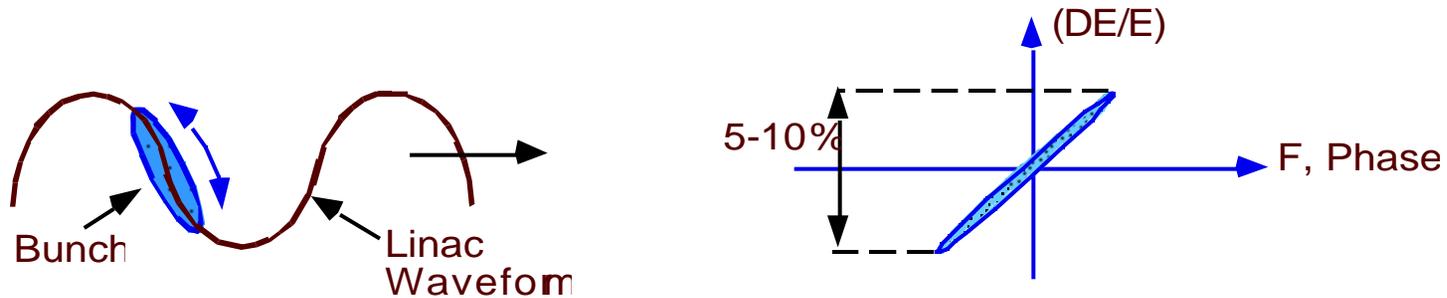


February 26, 1996

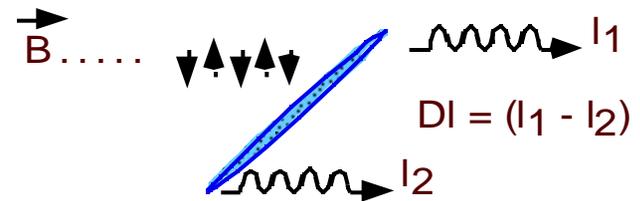


"Chirped" Low Energy Electron Beam Techniques

- Method of producing short electromagnetic pulses ($<< ps$) from long electron bunches (10 ps).
- Idea : - Produce a 50 MeV electron beam with a 5-10% systematic energy tilt (DE/E) on individual bunches. This can be achieved by differential phasing in linac sections which allows one to slide the electron beam on the linac RF waveform.



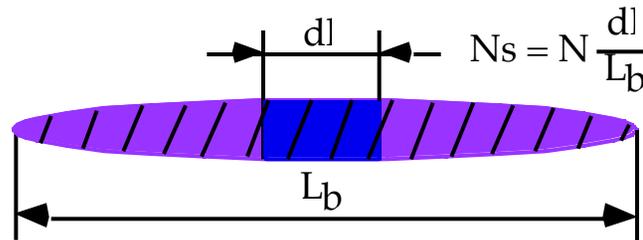
- Then send the beam through an undulator or compton backscatter against a high- power laser beam: Head and tail emit different wavelengths.
- Then send radiation through a dispersive element e.g. a "grating" fi Chirped Photon pulse.



Comments : Attractive, but cannot go far beyond the UV (few thousand A at best) since micro-undulator, given the status of current technology, can be built with a few mm period at best. Also pulse length is limited since it is difficult to put a "chirp" of more than 10% on a 50 MeV beam fi marginal sub-picosecond pulse generation. The Compton back scattering scenario requires a rather powerful and hefty laser making it somewhat unattractive.

Advantages

1. Strength of incoherent signal on other beam particles (noise) depends on the number of particles in a sample, N_s

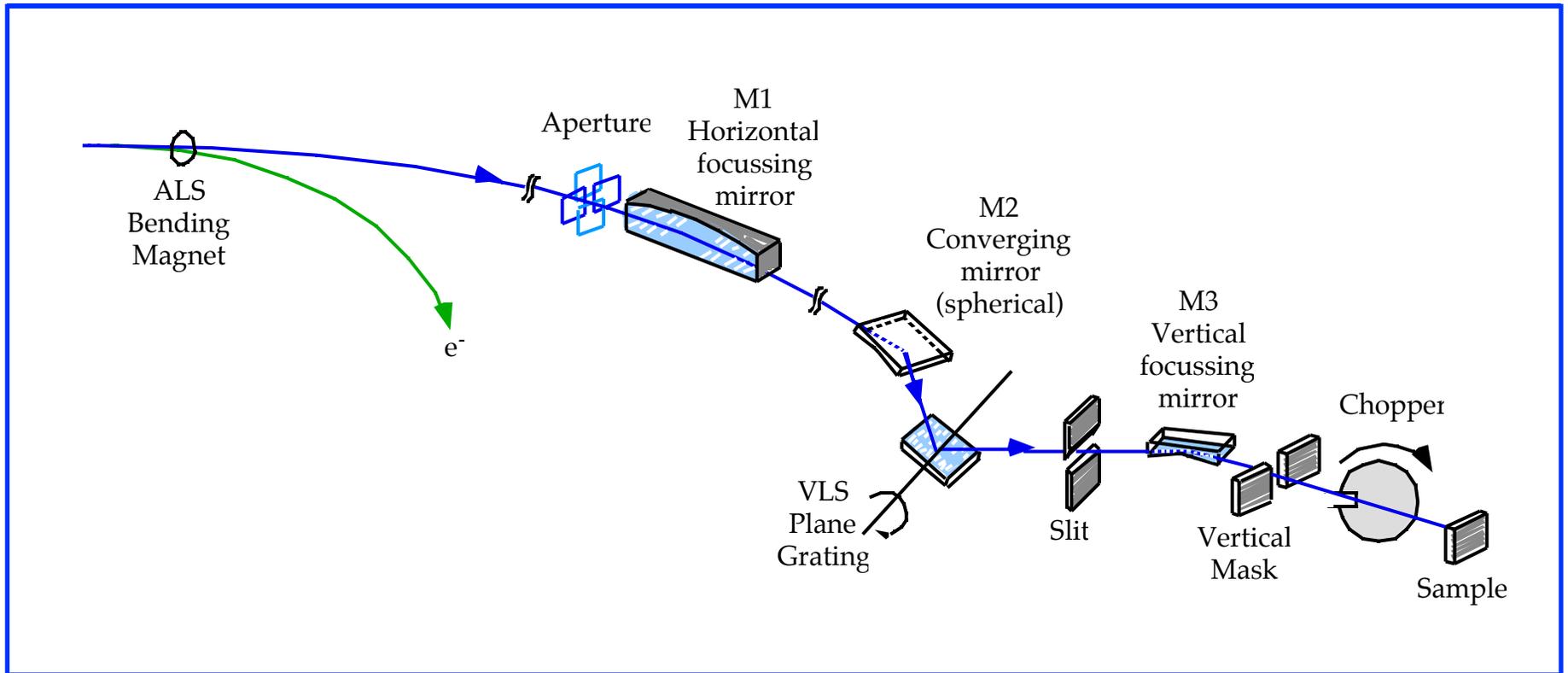


which is defined by the bandwidth of the overall system. (Compare 4×10^{13} Hz optical frequency bandwidth with 4×10^9 Hz microwave frequency bandwidth). Correspondingly, OSC has a potential to 10^4 faster damping than microwave stochastic cooling.

2. Alternatively, for the same damping time as in microwave stochastic cooling (very slow of OSC) we find a difference in the required amplifier power:

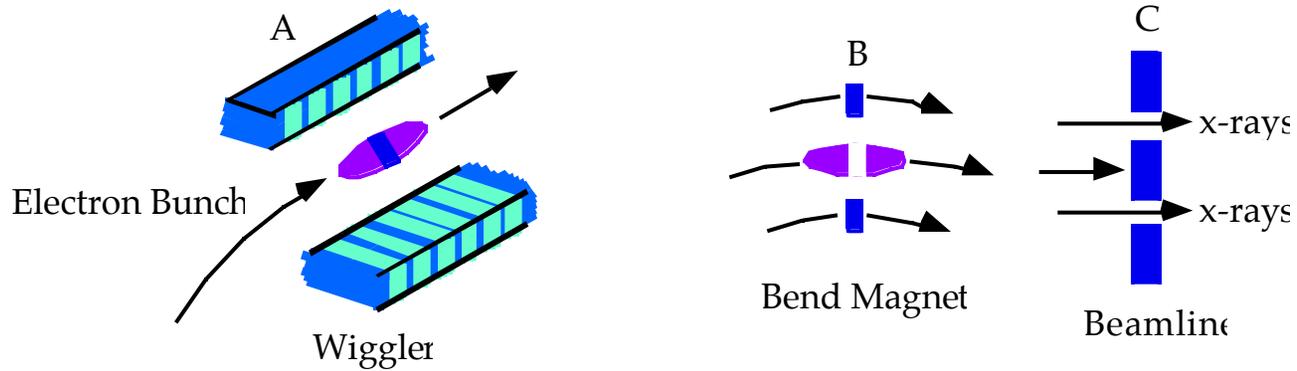
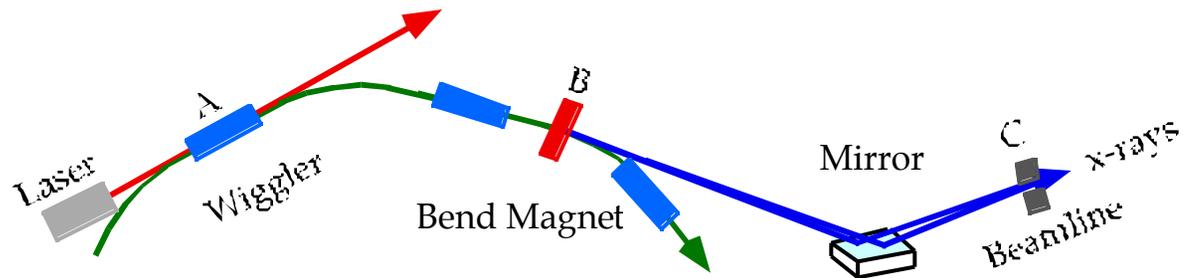
0.1 W for OSC

10^3 W for microwave cooling



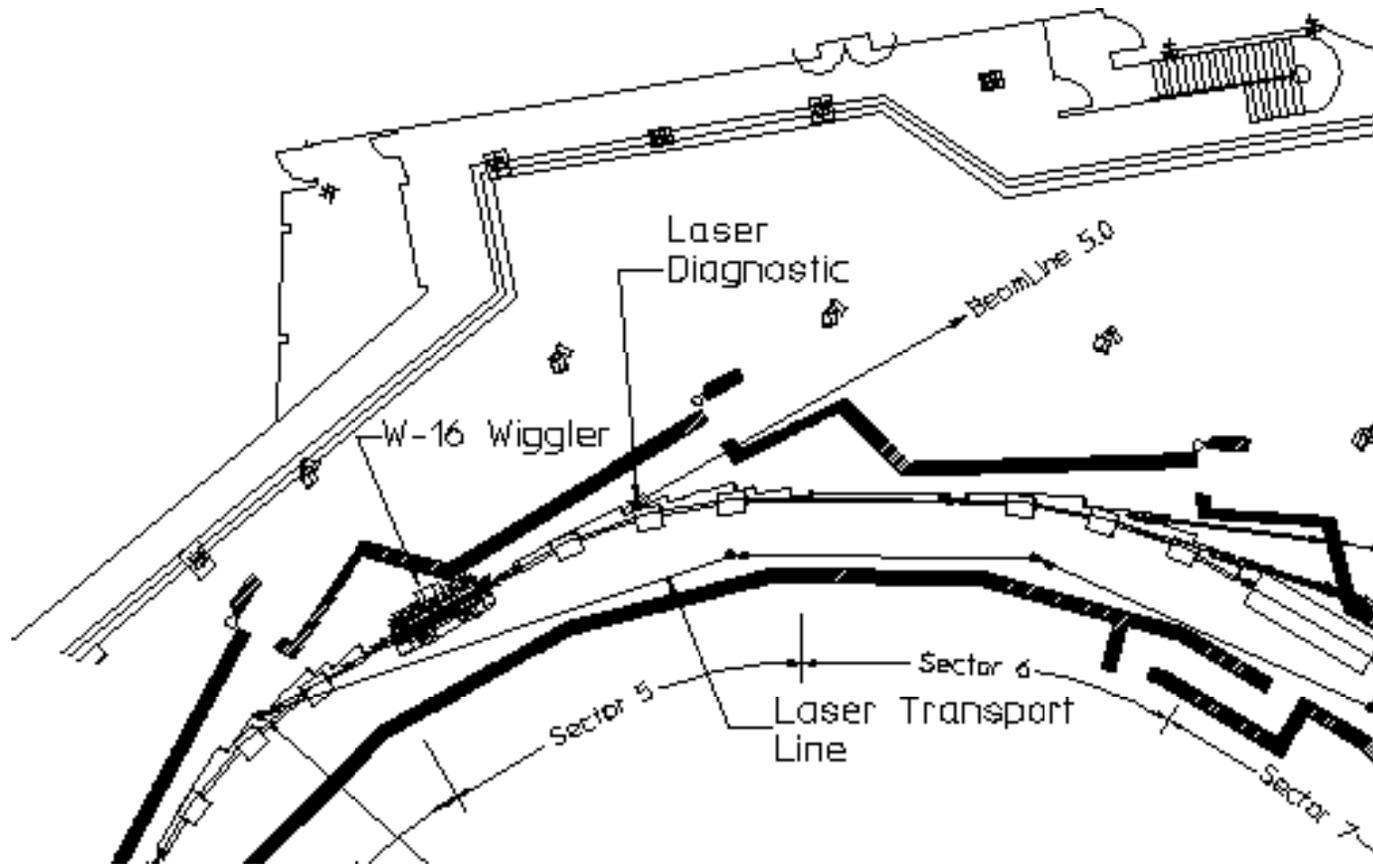


Bending Magnet



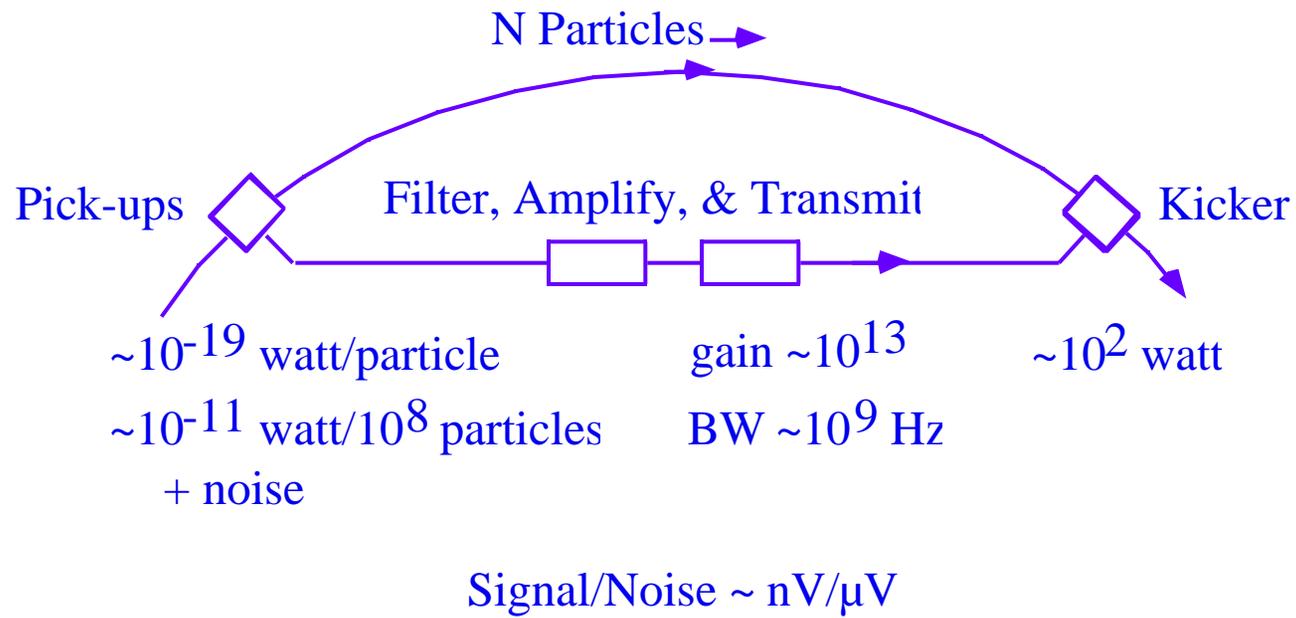


ALS Layout Implementation





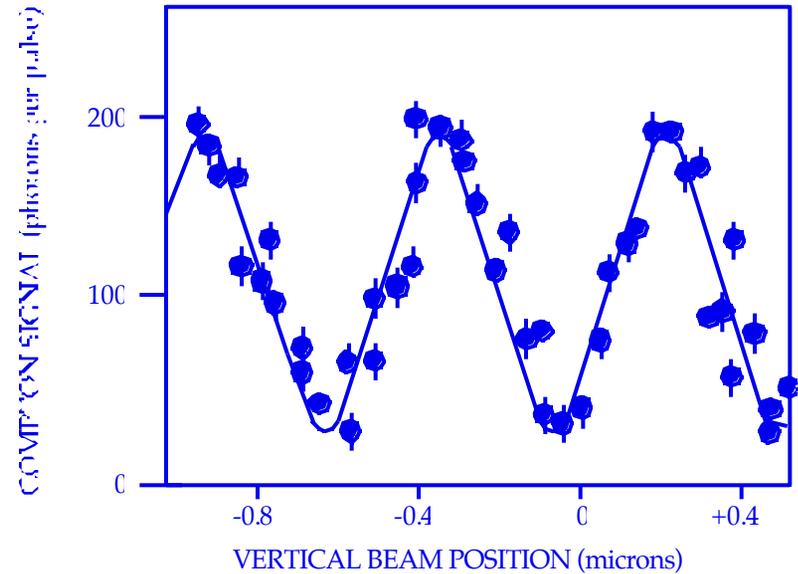
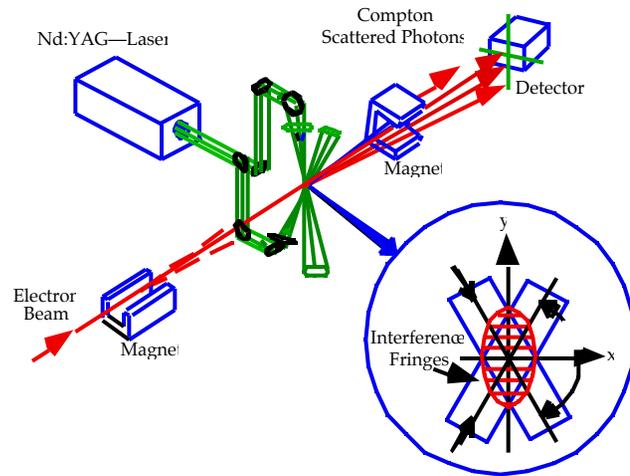
The Beam Cooling Scheme





Beam Monitoring in Ultrashort Dimensions

SLAC/FFTFB Results

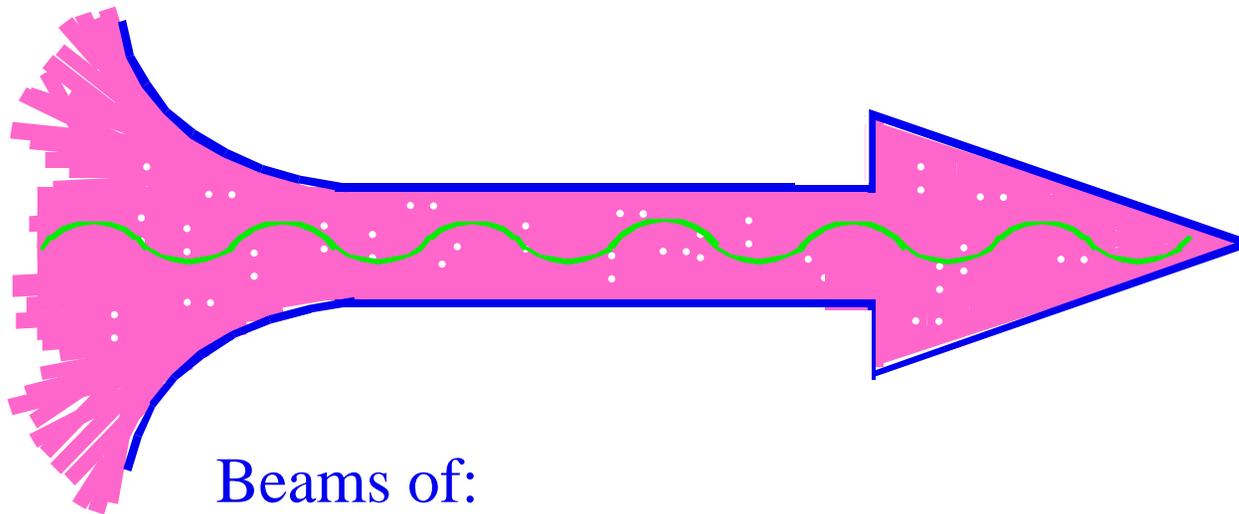


Measured RMS Spot Size : 70 nm



BEAMS

Directed and Focused Flow of Energy and Information

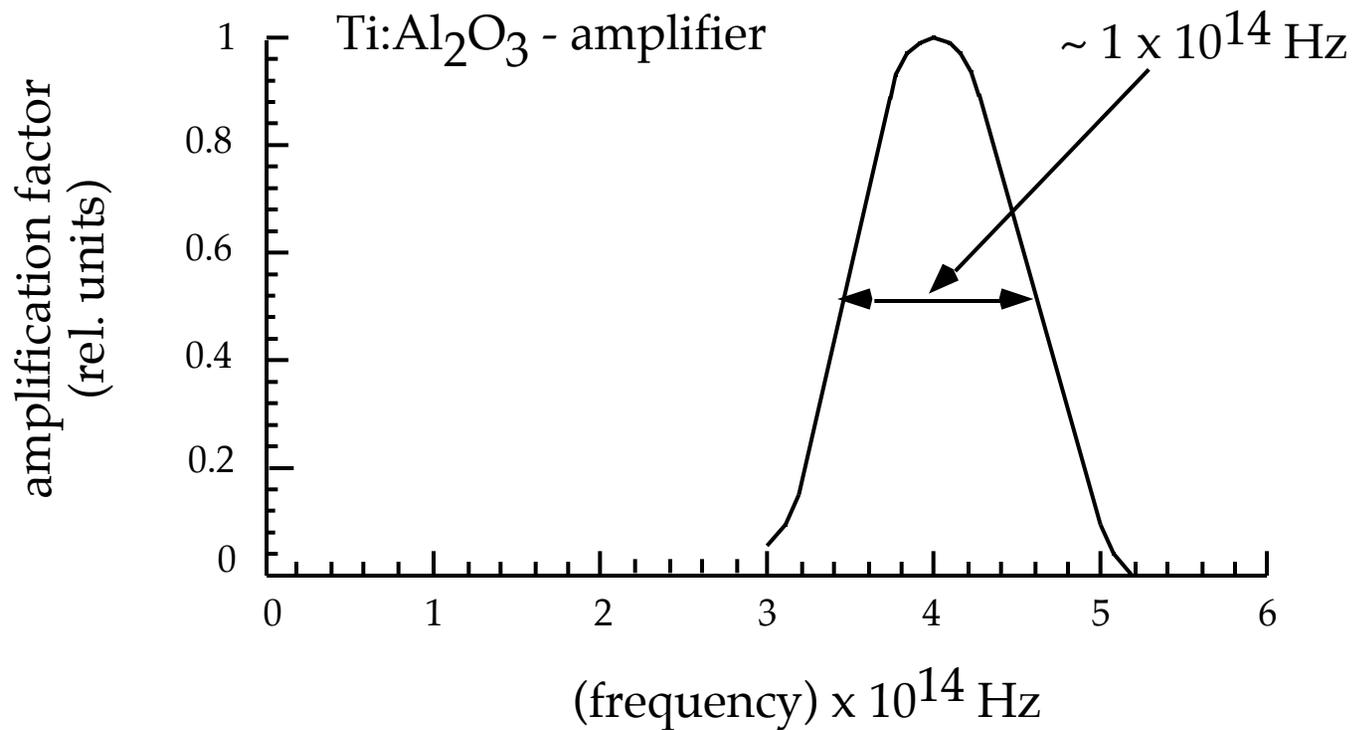


Beams of:

- Particles: electrons, protons, ions, ...
- Ultraviolet, Visible, Infrared, X-ray, **Photons**;
Radio **Waves**; Lasers

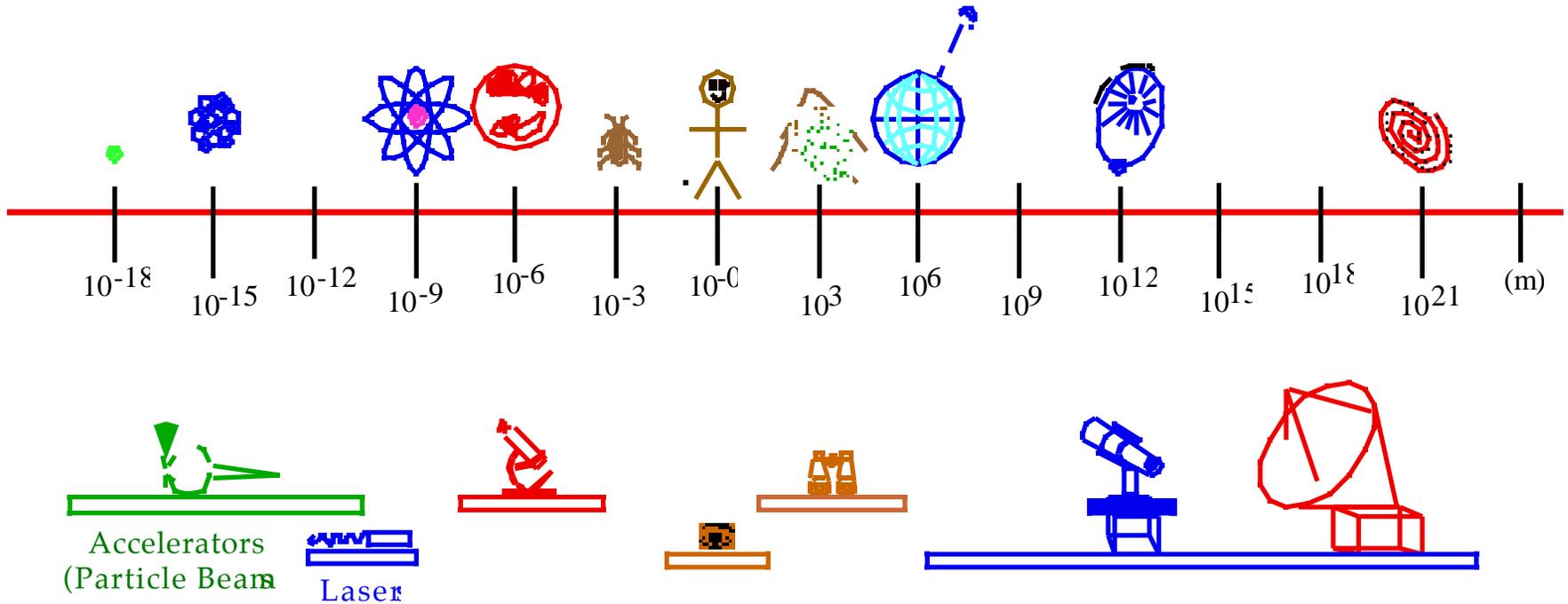


Broadband Optical Amplifiers (Ti:Al₂O₃, DYE)



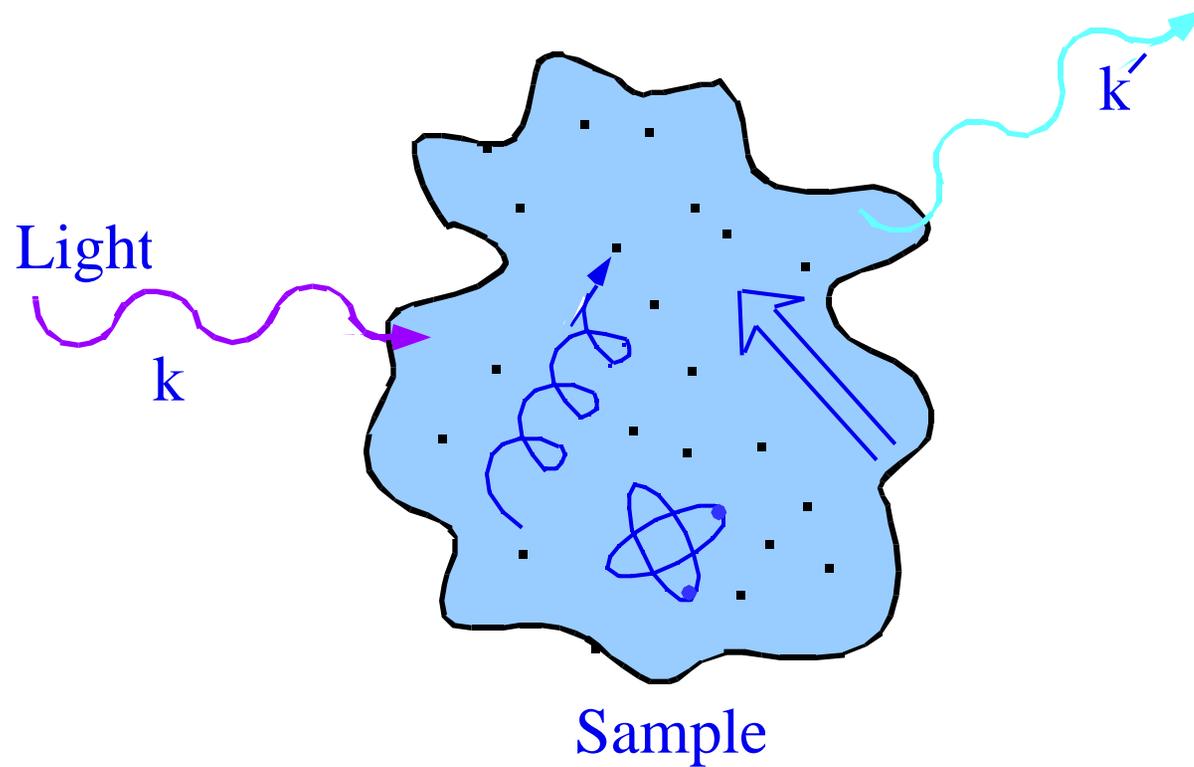


Probing at different scales — objects and instruments





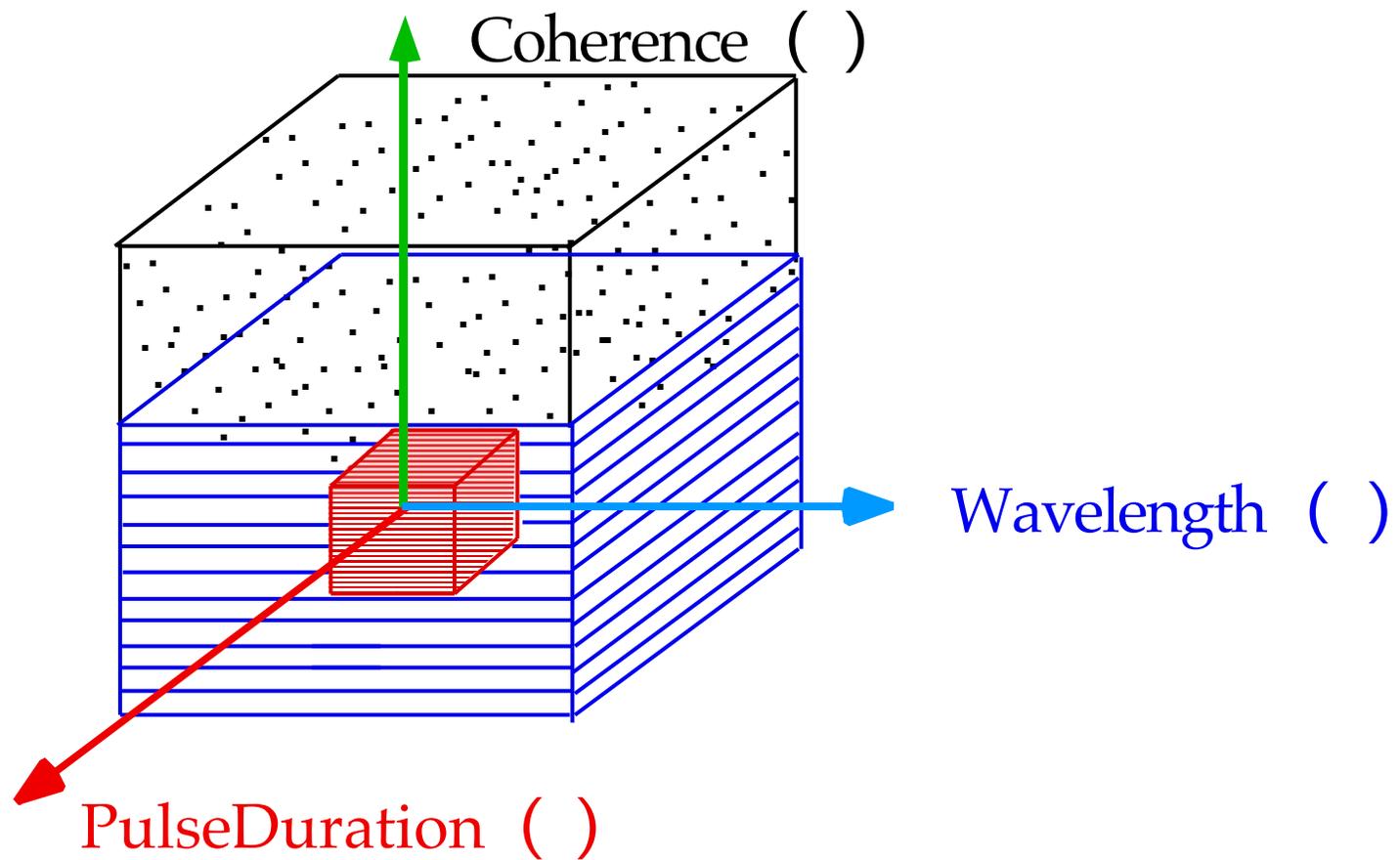
Condensed Matter, Biology, etc.





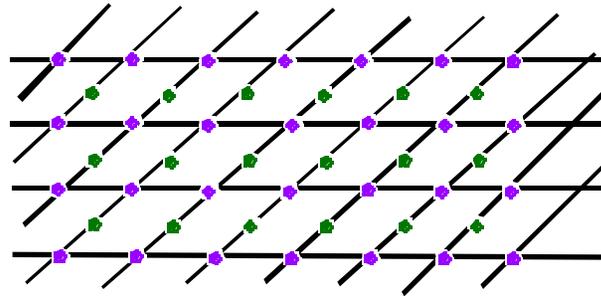
Major contributors to the topics of this talk :

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R. Schoenlein, (LBL)
A. M. Sessler, (LBL)
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K. Yokoya, (KEK)
A. Zholents, (LBL)
M. Zolotarev, (SLAC/LBL)

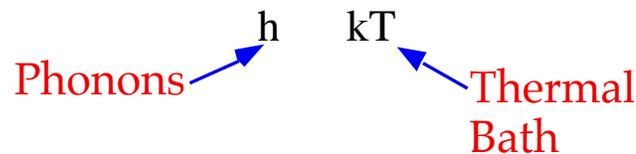




DYNAMICS ON A SURFACE



Lattice vibrations and 'Phonon' spectrum characterized by Debye time-scale :



Lattice relaxation time :

$$\tau = \hbar / kT \sim 100 \text{ fs @ room temp.}$$

e.g. PHASE TRANSITIONS like surface melting etc. take place on these 1 - 100 fs time-scale. EXTREMELY VALUABLE INFORMATION for SEMICONDUCTOR PHYSICS. e.g. Silicon



Necessity of Femtosecond Control for Future Accelerators

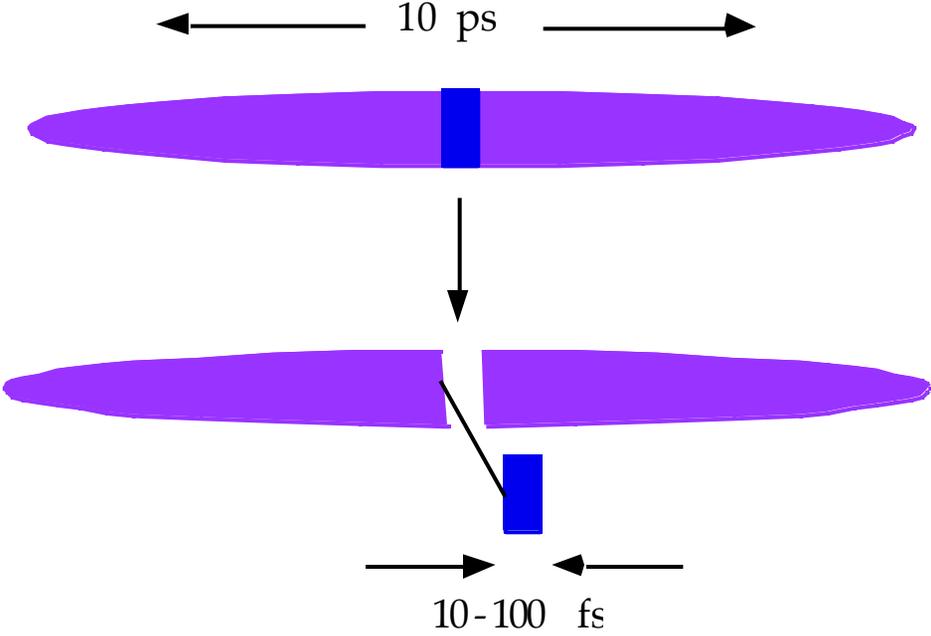
- Development of Femtosecond Kickers, Choppers, Bunch Rotators, etc.

Challenging job for beam physicists, but needs to be studied.

- Optical control of charged particle beam @ 300 THz
i.e. extract beam schottky noise @ 300 THz 3 fs from phase space.
Optical Stochastic Cooling.

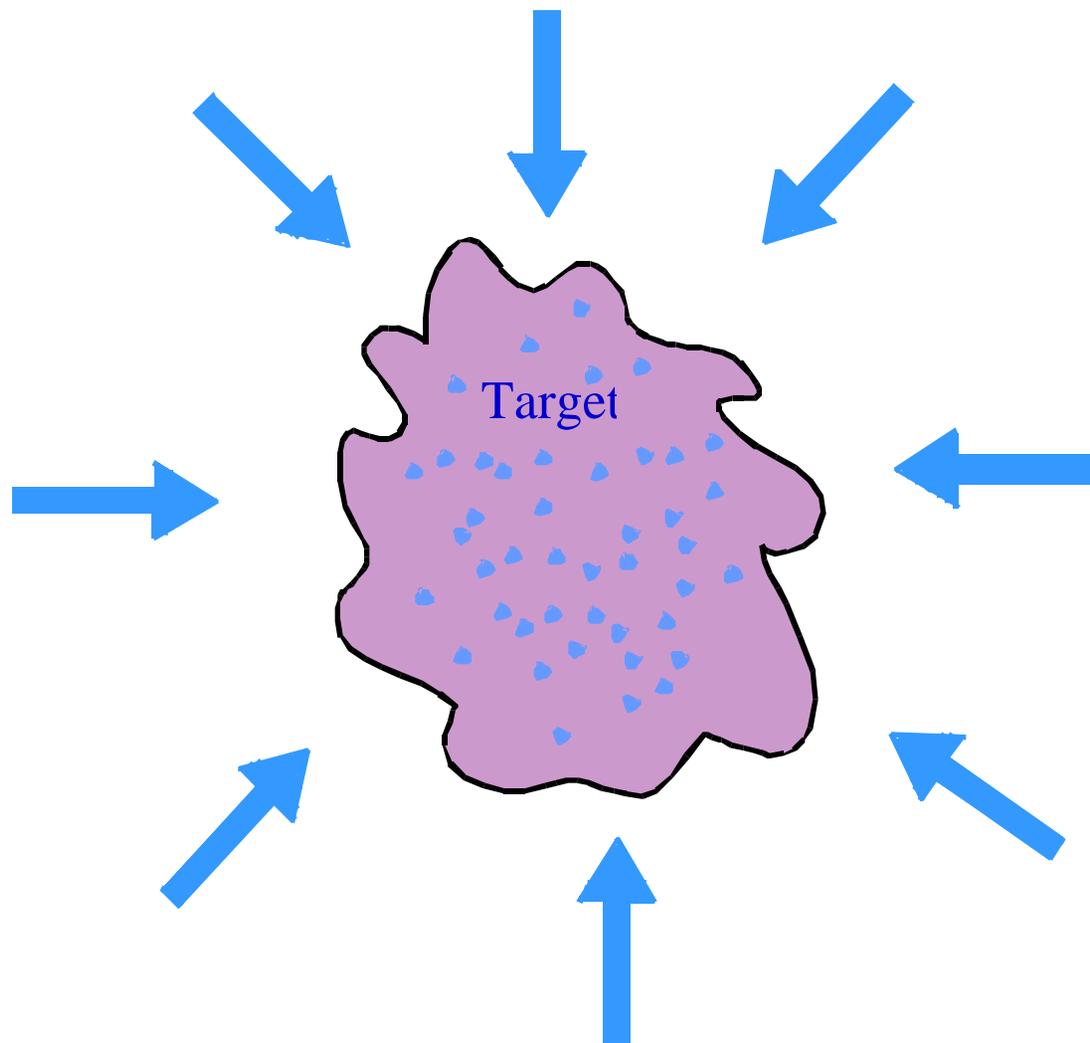


Femtosecond 'Tickle' and Slicing of Picosecond Electron Beams





Fusion

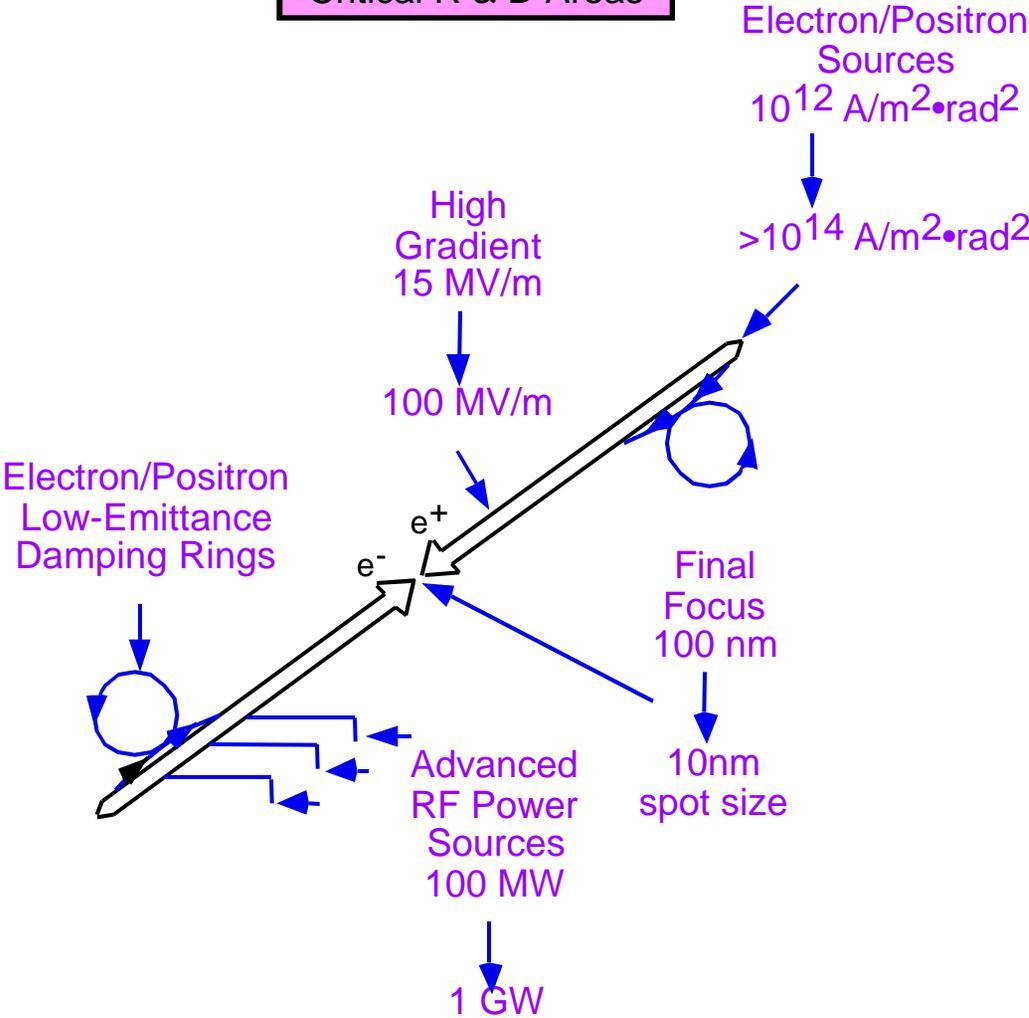




FUTURE $e^+ - e^-$ LINEAR COLLIDERS

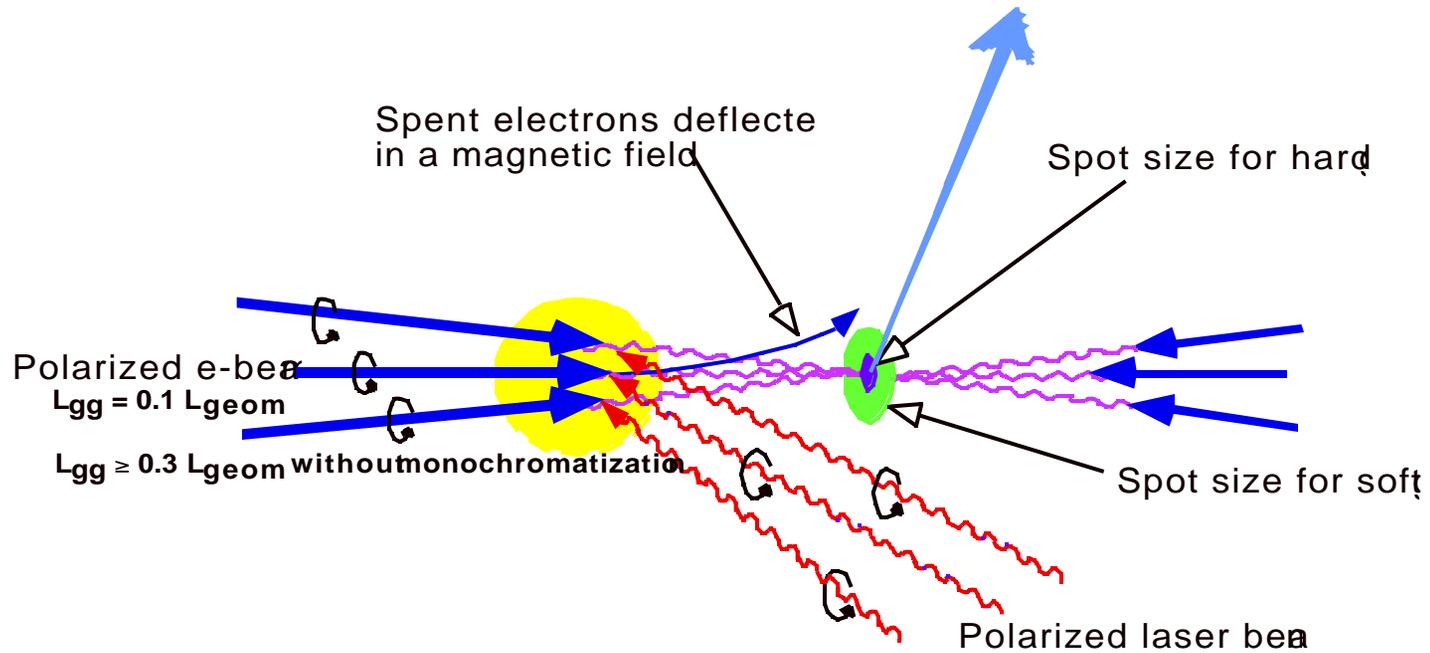
(High Gradient and Luminosity)

Critical R & D Areas





- Collisions of High Monochromaticity & Luminosity can be achieved





Harmonic Generation

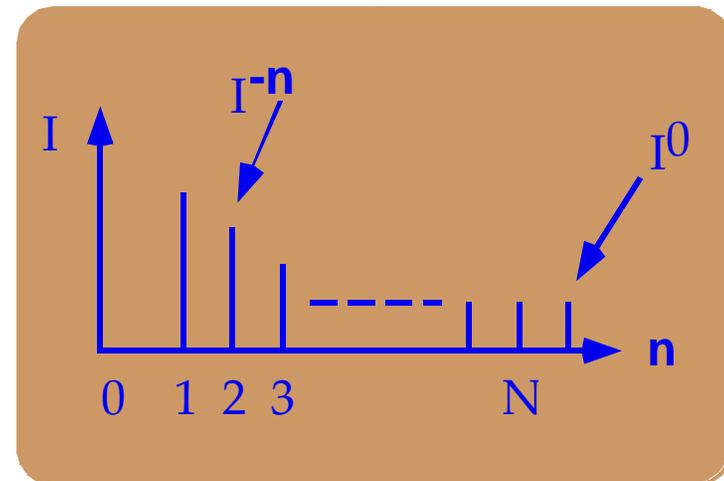
SHORT PULSE X-RAY SOURCES : GENERATION MECHANISMS

Coherent : directional

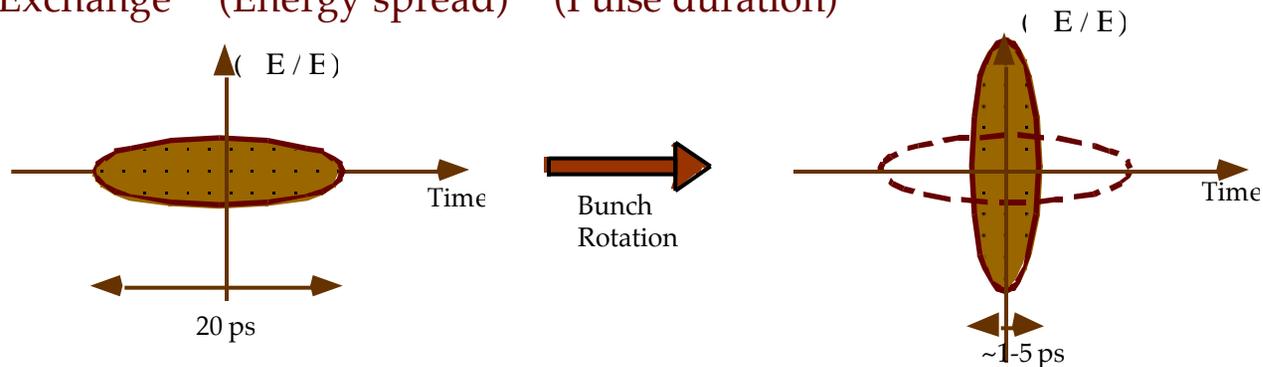
Short pulse

100 \AA for $I > 10^{15} \text{ W / cm}^2$

Inefficient ? $10^{-6} - 10^{-11}$



- Insert a special rf cavity in a storage ring
- Quickly rotate an electron pulse in phase-space by 90° in a single turn
- Exchange " (Energy spread) (Pulse duration)



Comments :

The storage ring has to be operated in a single bunch mode, with a repetition rate of ~ 1 MHz, since rf cavities cannot work in the fast multibunch mode.

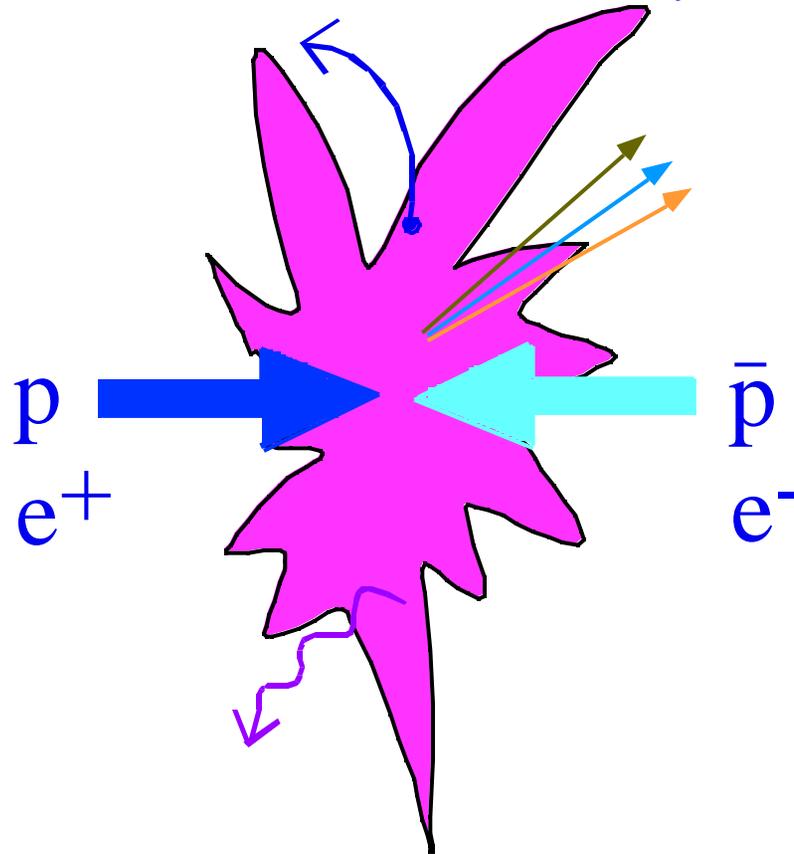
Shortest pulse length possible will be in the few picosecond range-not a great deal

- Compton scattering a femtosecond visible laser pulse against 1.5 GeV beam, one would generate too short a wavelength ($\ll 1 \text{ \AA}$) to be useful, since $\lambda \approx 3000 \text{ \AA}$. Even with infra-red, the scattered radiation is too short in wavelength. Besides the mechanism of colliding a laser beam with the electron beam in a storage ring vacuum tank is cumbersome, to say the least.



High Energy Physics

(i.e. Particle & Nuclear Physics):

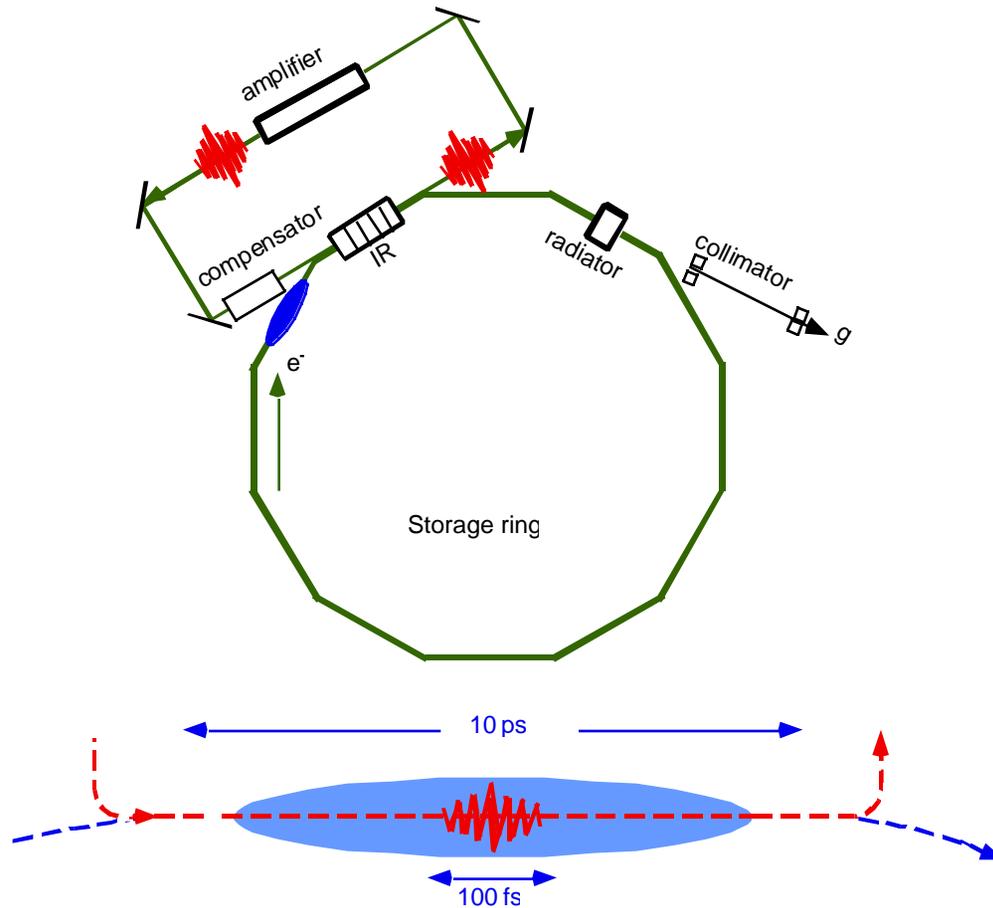


Fireball of pure energy nucleating into matter and waves again.

Implementation in the ALS

A.A. Zholents & M. Zolotarev,
Phys. Rev. Lett. 76, 916-918 (1996)

Femtosecond Slicing in a Storage Ring





SHORT PULSE X-RAY SOURCES : GENERATION MECHANISMS

- **Laser produced plasma sources**
- **Harmonic Generation**
- **Bunch rotation in a storage ring**
- **Femtosecond slicing in a storage ring**
- **Laser scattering from electron beam**



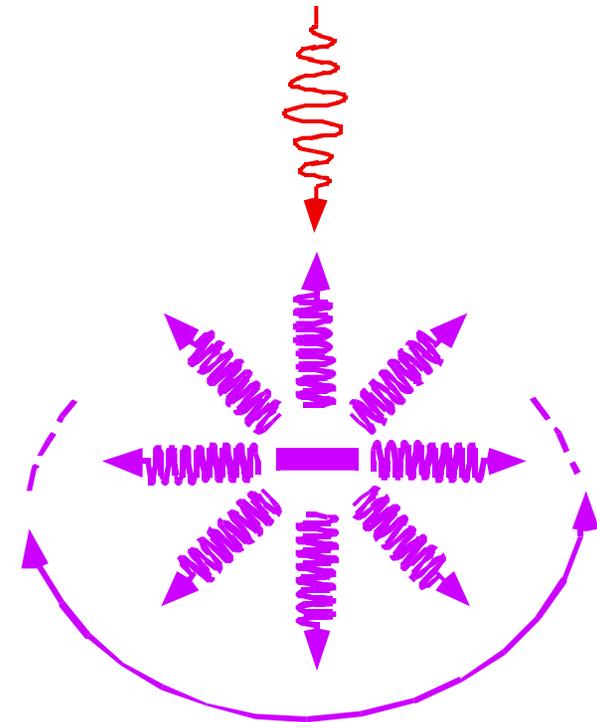
Laser Acceleration

- Lasers : well-known to have high electric and magnetic fields
- Lasers can be coupled to particle beam for net longitudinal acceleration
 - in free space in presence of boundaries and apertures
 - in free space without boundaries via nonlinear higher order mechanisms and in presence of magnetic fields
 - via direct coupling of lasers to a plasma-like medium



Laser produced plasma sources

- Line emission, recombination radiation and bremsstrahlung
- Incoherent but bright
- Efficient in sub-keV region ~ ps : -s ??
- Large solid angle

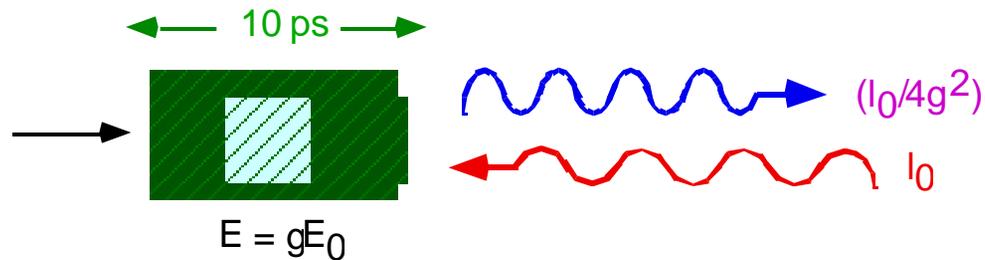


4 Π Solid angle



Laser scattering from electron beam

SHORT PULSE X-RAY SOURCES : GENERATION MECHANISMS

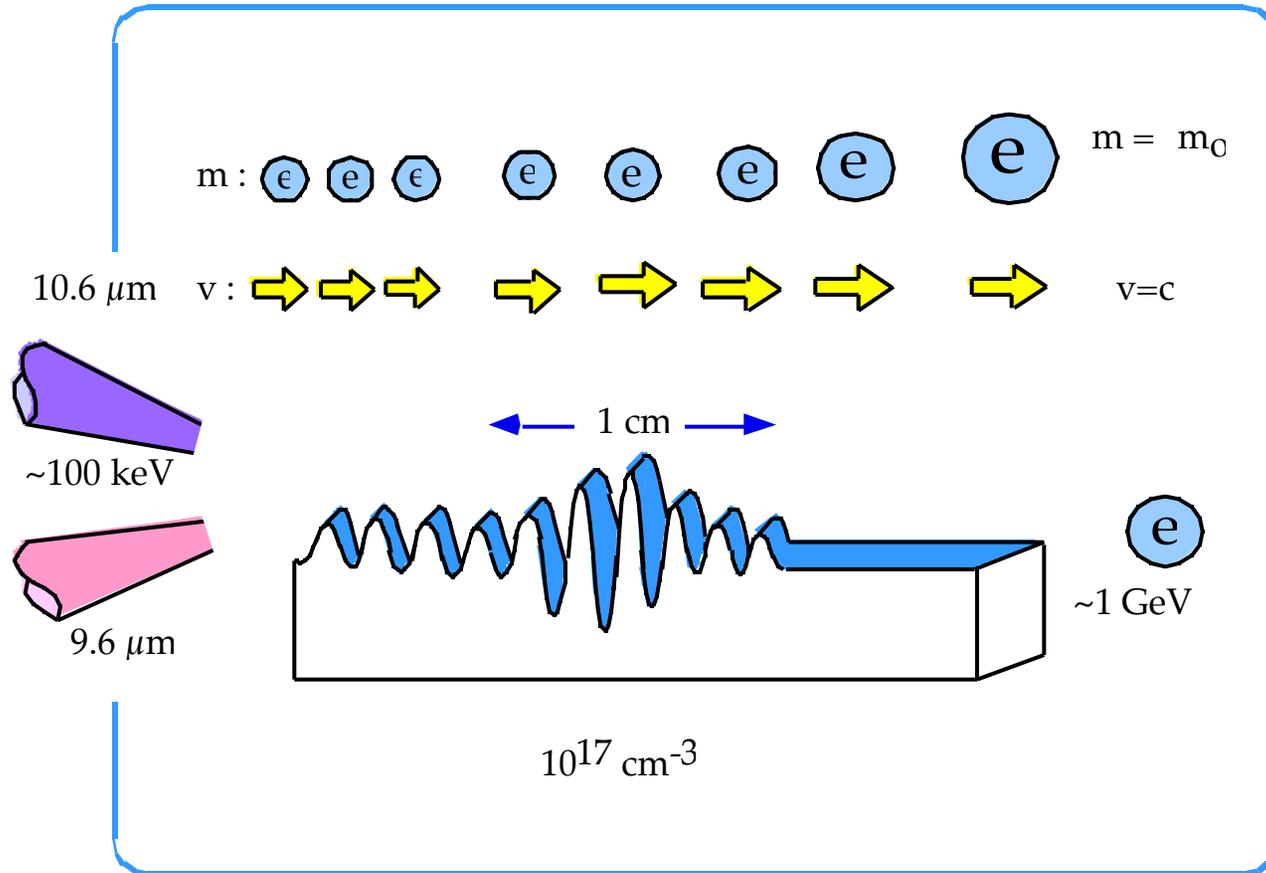


Still limited to "picosecond" time-scales :
Photon Pulse length ~ Longer of (e^- , g) Pulse



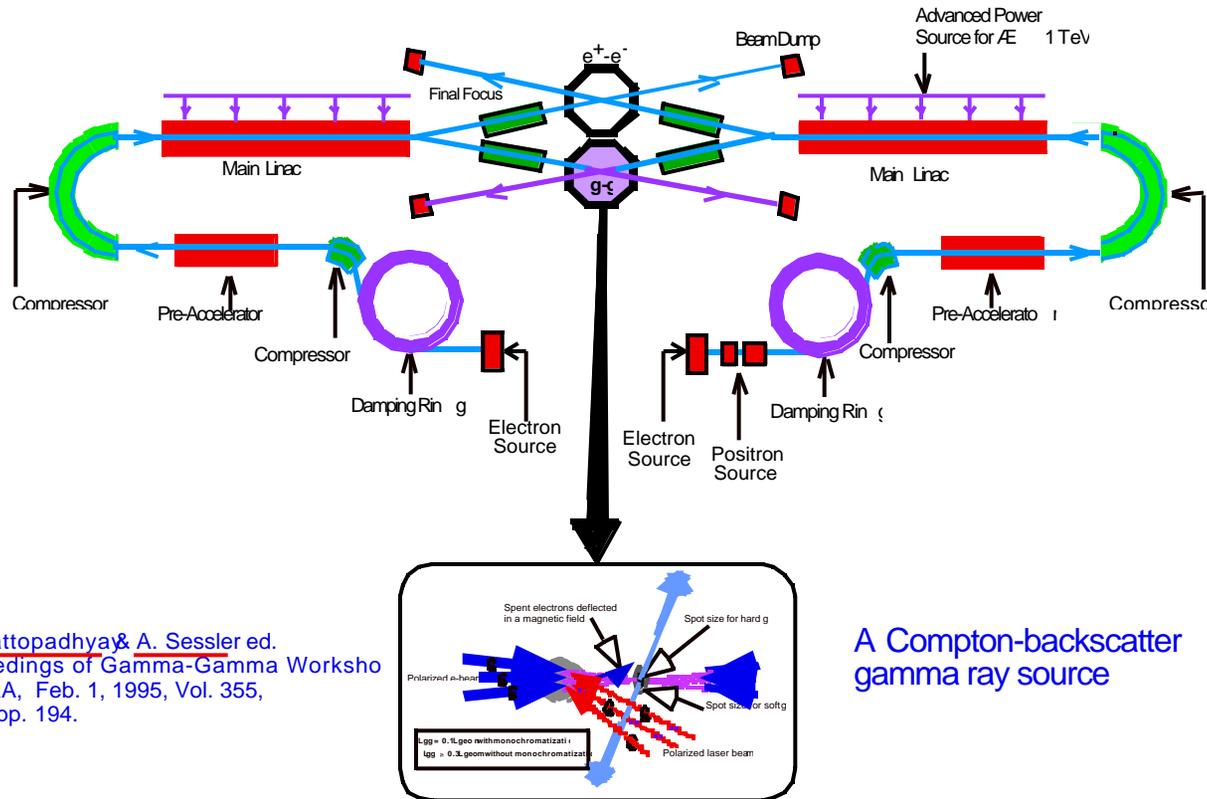
Lasers in Ultrafast Processes

- Necessity of THz, femtosecond control for future accelerators
- Study of ultrafast (femtosecond) processes in nature with resolution of nuclear motion (x-rays)





Exotic Collisions : Gamma-Gamma Collider



S. Chattopadhyay & A. Sessler ed.
 Proceedings of Gamma-Gamma Workshop
 NIMPR, Feb. 1, 1995, Vol. 355,
 No. 1, pp. 194.

A Compton-backscatter hard
 gamma ray source



Luminosities in g-g Collision (V. Telnov)

	A	B	C	D	E	F	G
L_{ee}/L_{geom}	0.2	0.19	0.15	0.16	0.12	0.096	0
$L_{ee}(z>0.65)/L_{geom}$	0.12	0.114	0.086	0.091	0.064	0.046	0
L_{ge}/L_{geom}	1.12	1.04	0.93	0.52	0.79	0.706	0.1
$L_{ge}(z>0.65)/L_{geom}$	0.26	0.24	0.2	0.22	0.18	0.143	0.017
L_{gg}/L_{geom}	1.23	1.22	1.16	0.38	1.08	1.05	0.37
$L_{gg}(z>0.65)/L_{geom}$	0.116	0.112	0.105	0.104	0.103	0.098	0.09
$L_{gg}(z>0.75)/L_{geom}$	0.057	0.0545	0.0514	0.051	0.05	0.046	0.051
$q_{y,max}[\text{mrad}]$	8	8	8	8	8	8	2.5
E_{min}	3	3	3	3	3	3	3

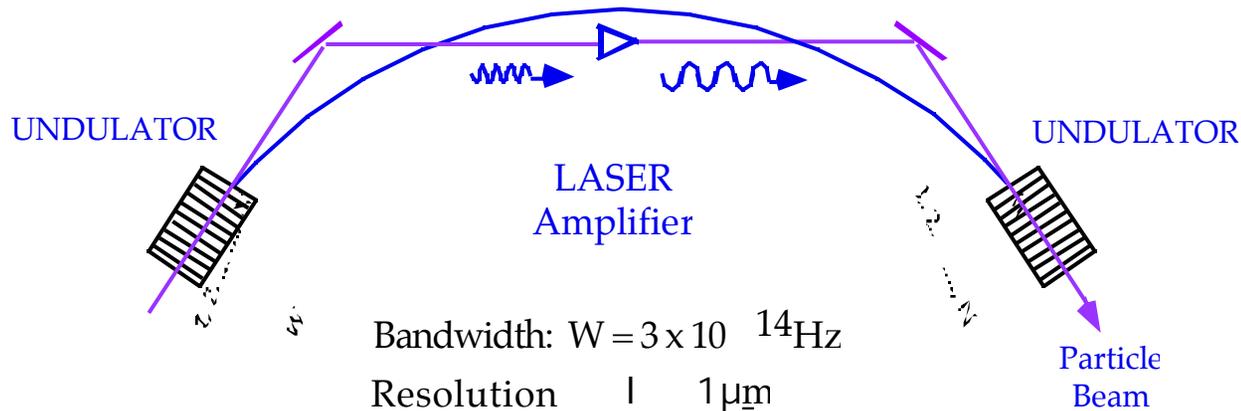
A no magnet deflection $D_y = 0.25 s_y$
 B " $D_y = 0.5 s_y$
 C " $D_y = 0.75 s_y$
 D
 E " $D_y = 1 s_y$
 F " $D_y = 1.25 s_y$
 G with magnet deflection, $b = 0.78\text{cm}$, $B = 10\text{ kGs}$



Optical Stochastic Cooling

The Idea

A. Mikhailichenko & M. Zolotarev,
Phys. Rev. Lett. Z, (25), 4146 (1993).



Bandwidth: $W = 3 \times 10^{14} \text{ Hz}$

Resolution $l \quad 1 \mu\text{m}$

Gain: $g \quad 10^4$

#Photons/charged particle $\sim N W K^2$

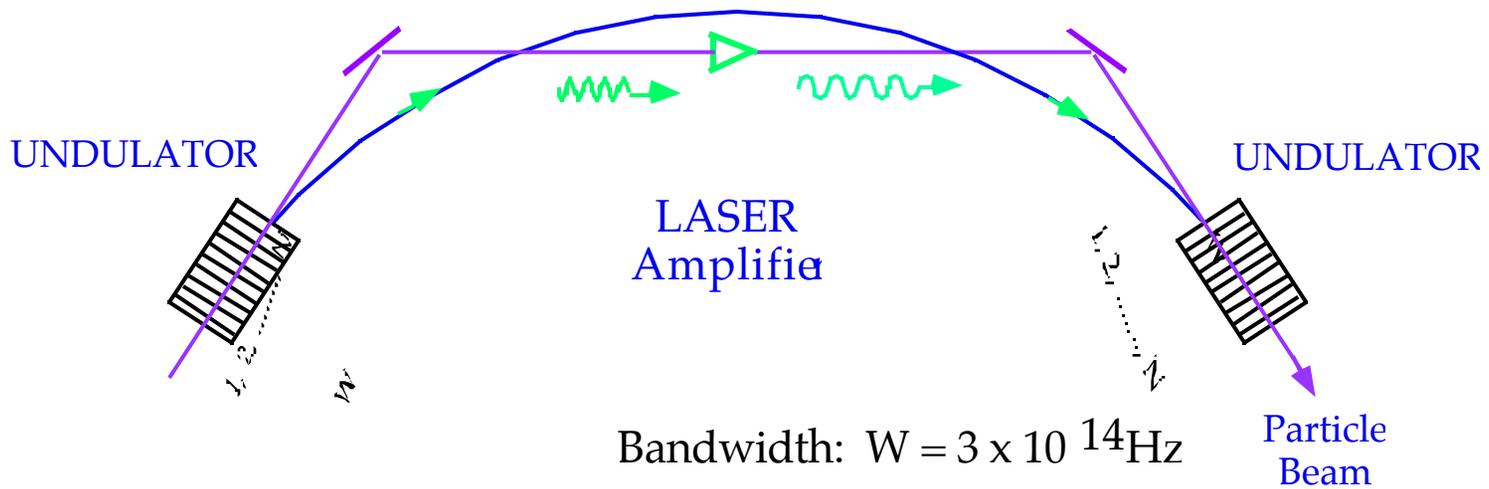
Weak undulator: $K \sim 0.1 \quad n/n_e \sim 1/137$

Strong undulator: $K \sim 1 \quad n/n_e \sim 1$

- Quantum Noise
- Signal/Noise
- Coherent Radiation



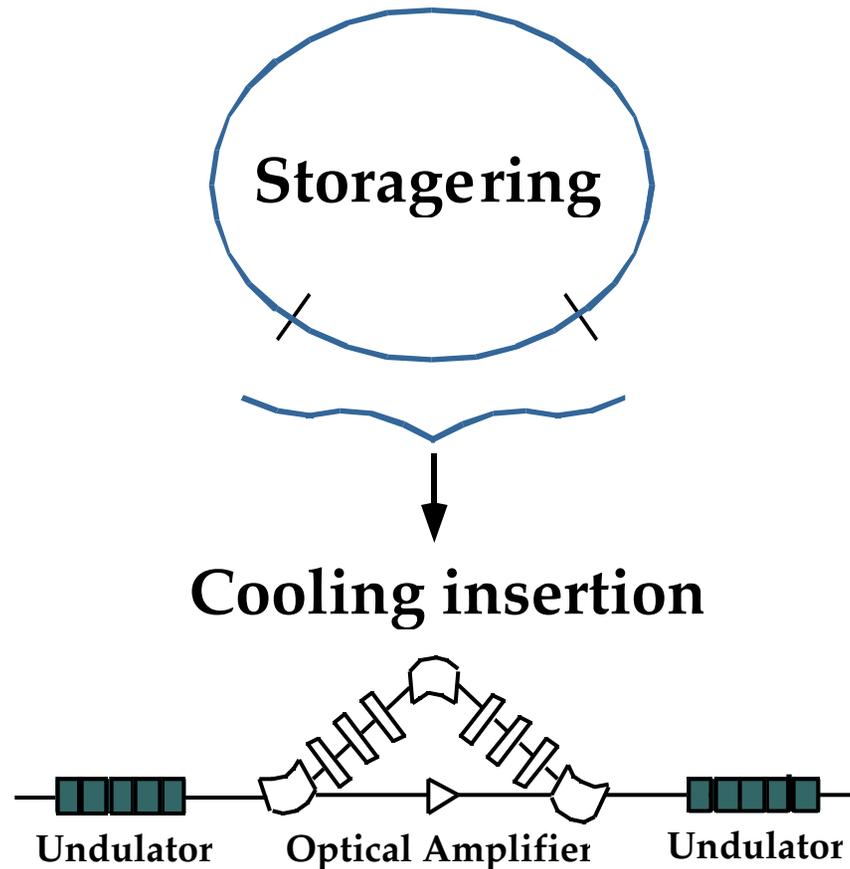
Optical Stochastic Cooling



Resolution: $l \quad 1 \mu\text{m}$
Gain: $g \quad 10^4$



Optical Stochastic Cooling



Bypass forces each particle to meet its own amplified radiation in the second undulator where it receives a "coherent" energy kick due to interaction with this radiation.

A. Zholents & M. Zolotarev,
Phys. Rev. E50 (4), 3087 91994)



OUTLINE

- Prelude : Particle Beams and Lasers
- Lasers in Ultrafast Processes
 - Radiation Sources
 - Femtosecond Synchrotron Radiation in a Storage Ring
 - Femtosecond x-rays by Thomson Scattering
 - Linear Coherent Light Source
 - Optical Stochastic Cooling
- Lasers in Particle Physics
 - Diagnostics : Beam Monitoring in Ultrashort Dimensions
 - Exotic Collisions : Gamma-Gamma Collider
- Lasers for Particle Acceleration
- OUTLOOK



OUTLOOK

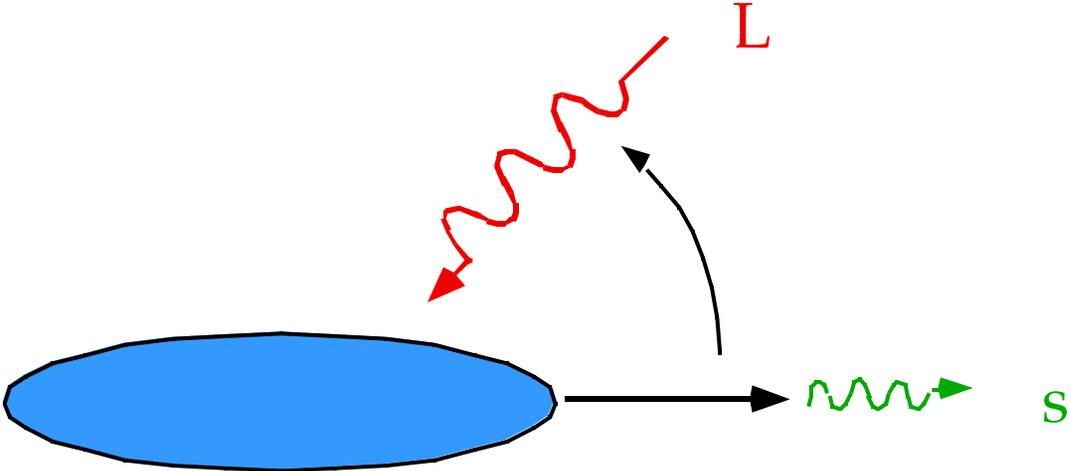
Modern lasers, linacs and high brightness (low emittance) storage rings offer various schemes of manipulation of mutually interacting charged particle and optical beams with novel applications in High Energy Collisions and Advanced Radiation Sources raised to a new level of sophistication.

The new generation of colliders and radiation sources already available and planned will clearly offer some of these very exciting possibilities !!

Let us not miss these opportunities !!!



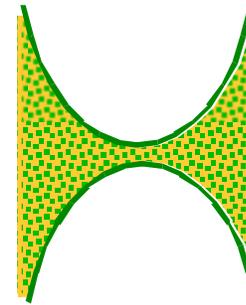
THOMSON/ COMPTON SCATTERING



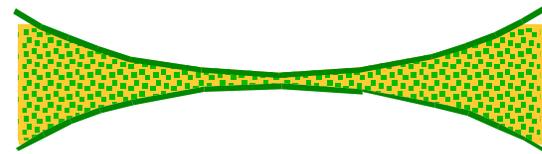
$$= C$$

$$s = \frac{L}{2} f(\theta)$$

- at a "sharp" waist for laser scattering



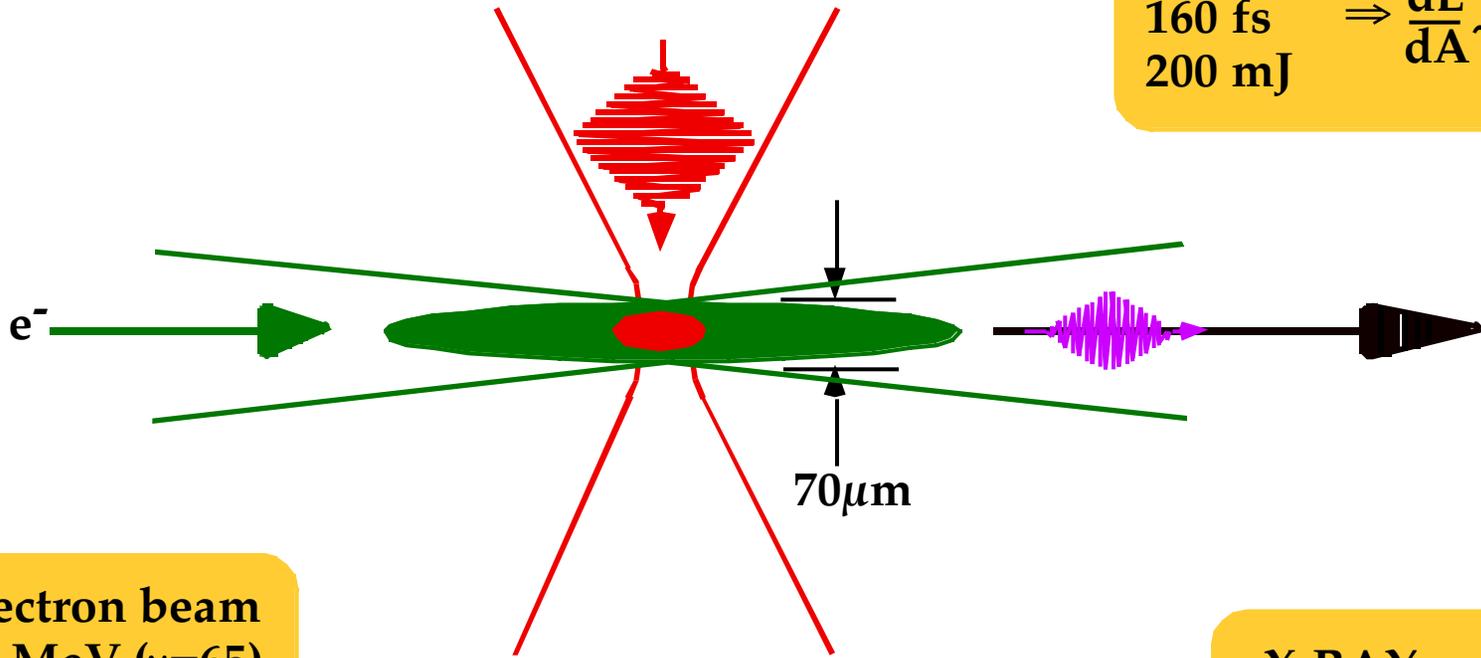
- at a "long" waist for micro-undulators





90° Thomson Scattering

laser pulse
800 nm
160 fs $\Rightarrow \frac{dE}{dA} \sim 10^{16} \text{W/cm}^2$
200 mJ



electron beam
35 MeV ($\gamma=65$)
2 nC/pulse
15 ps

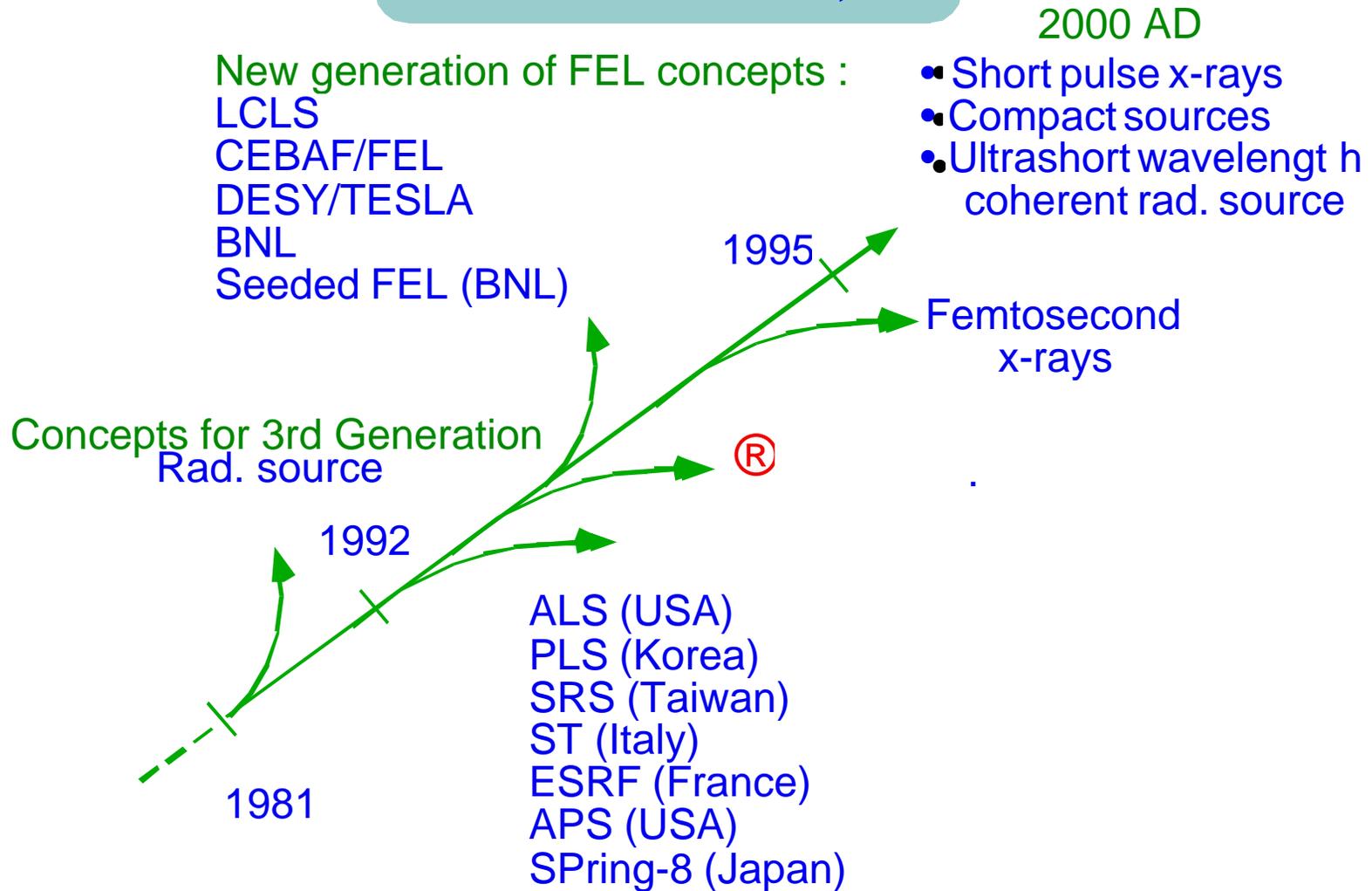
$$\alpha = \frac{L}{2}^2$$

X-RAYS
200 fs
1 A (12keV)
 10^6 photons/sec
 $\theta \sim 10$ mrad (10% BW)



Where From ? Where To ?

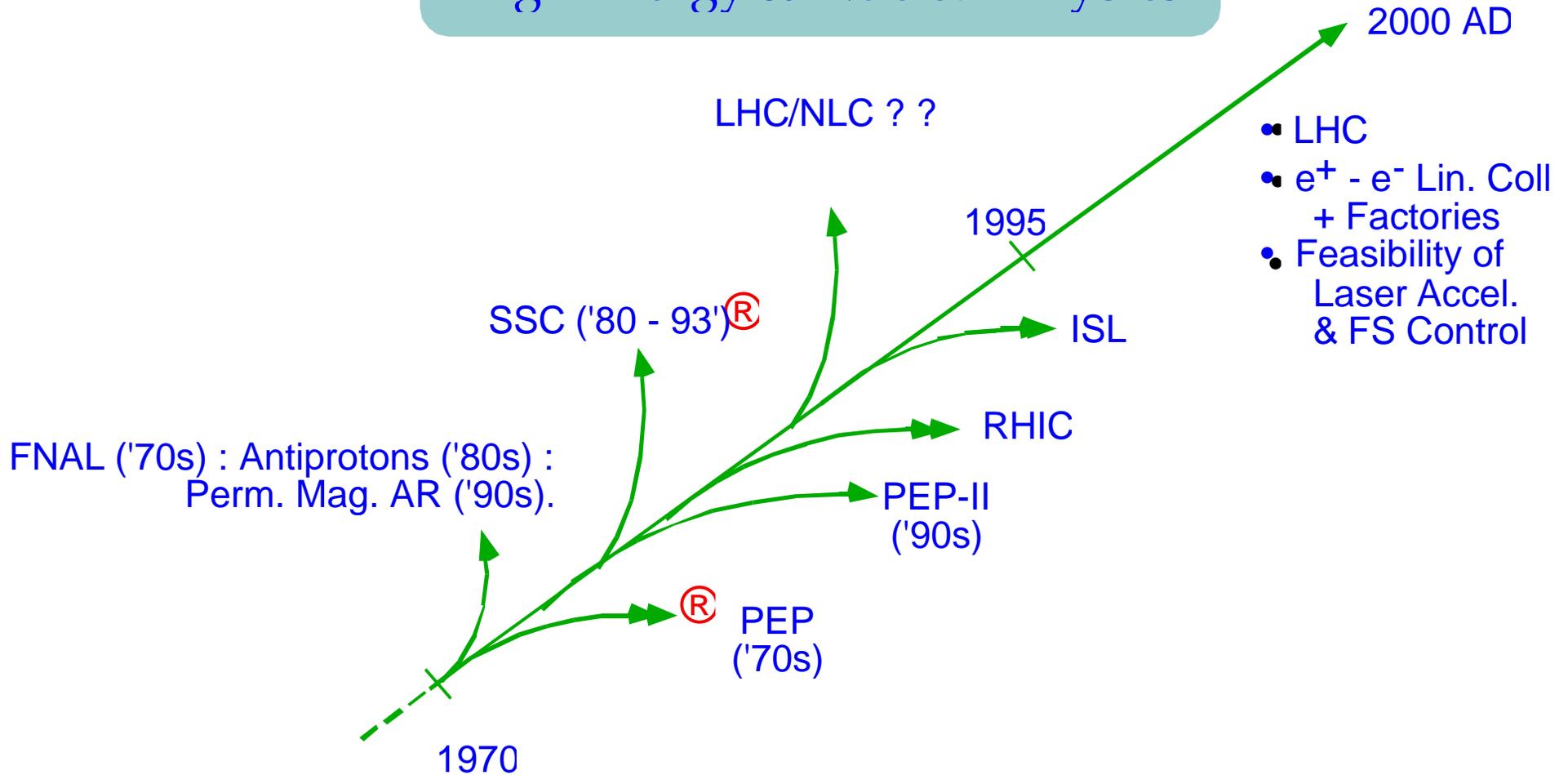
Radiation Sources, etc.





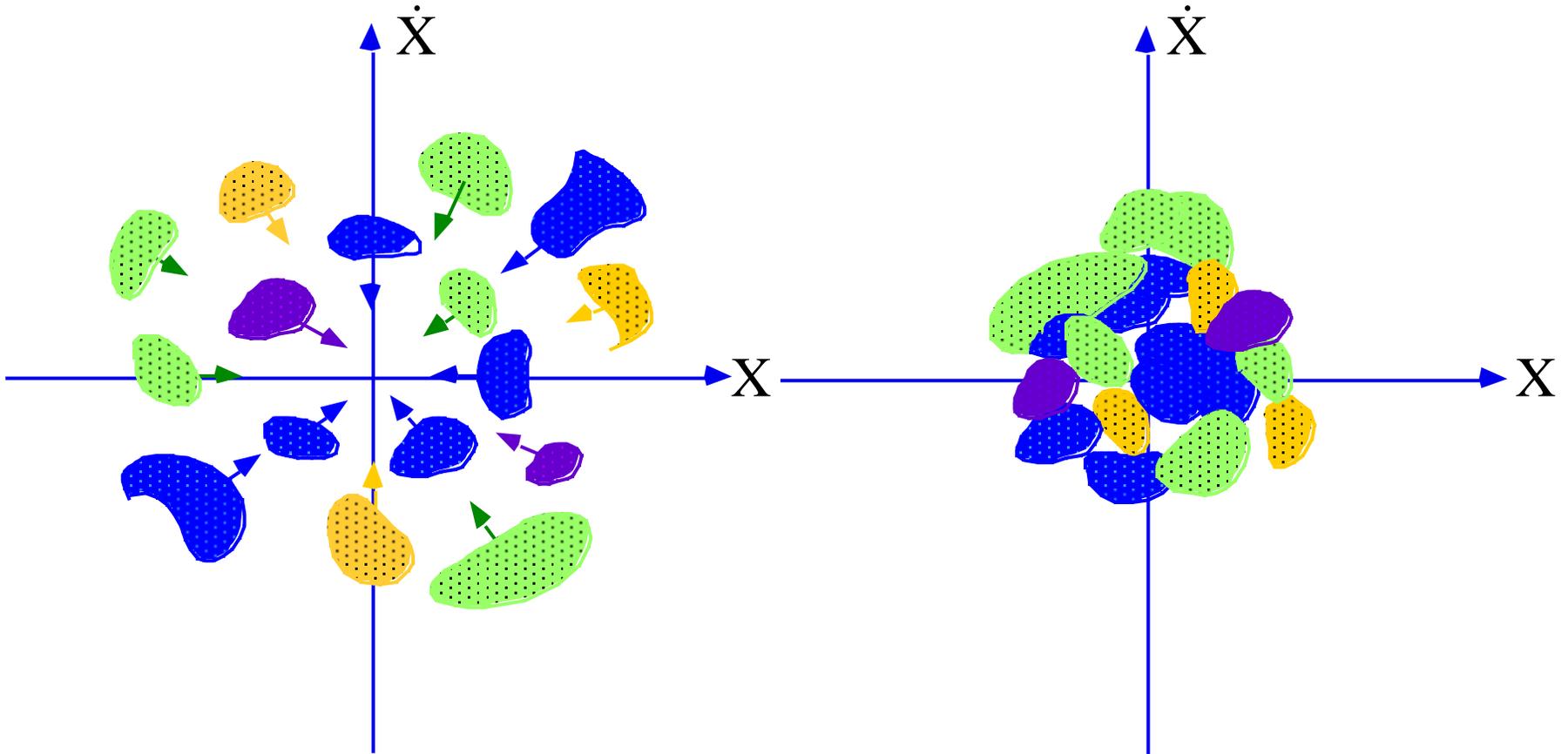
Where From ? Where To ?

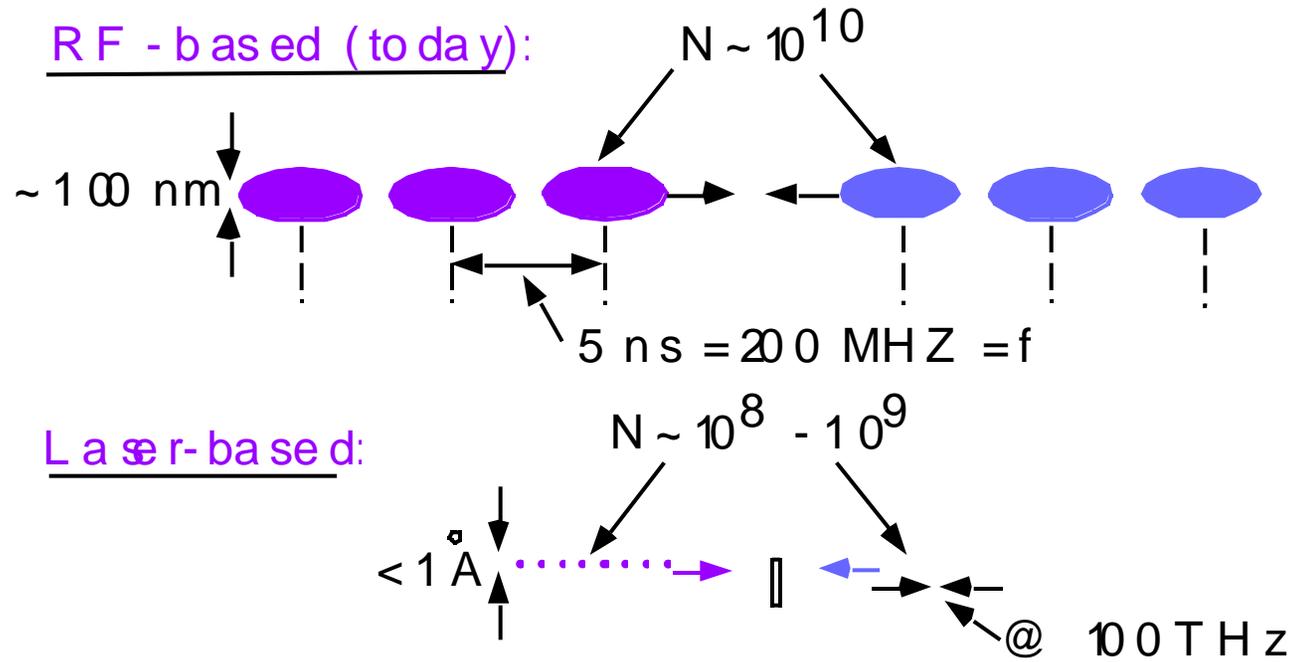
High Energy & Nuclear Physics





Phase-Space Cooling in Any One Dimension





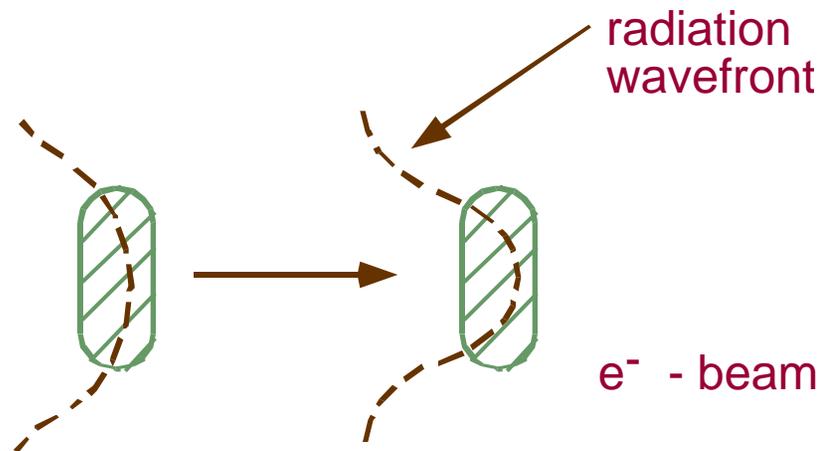


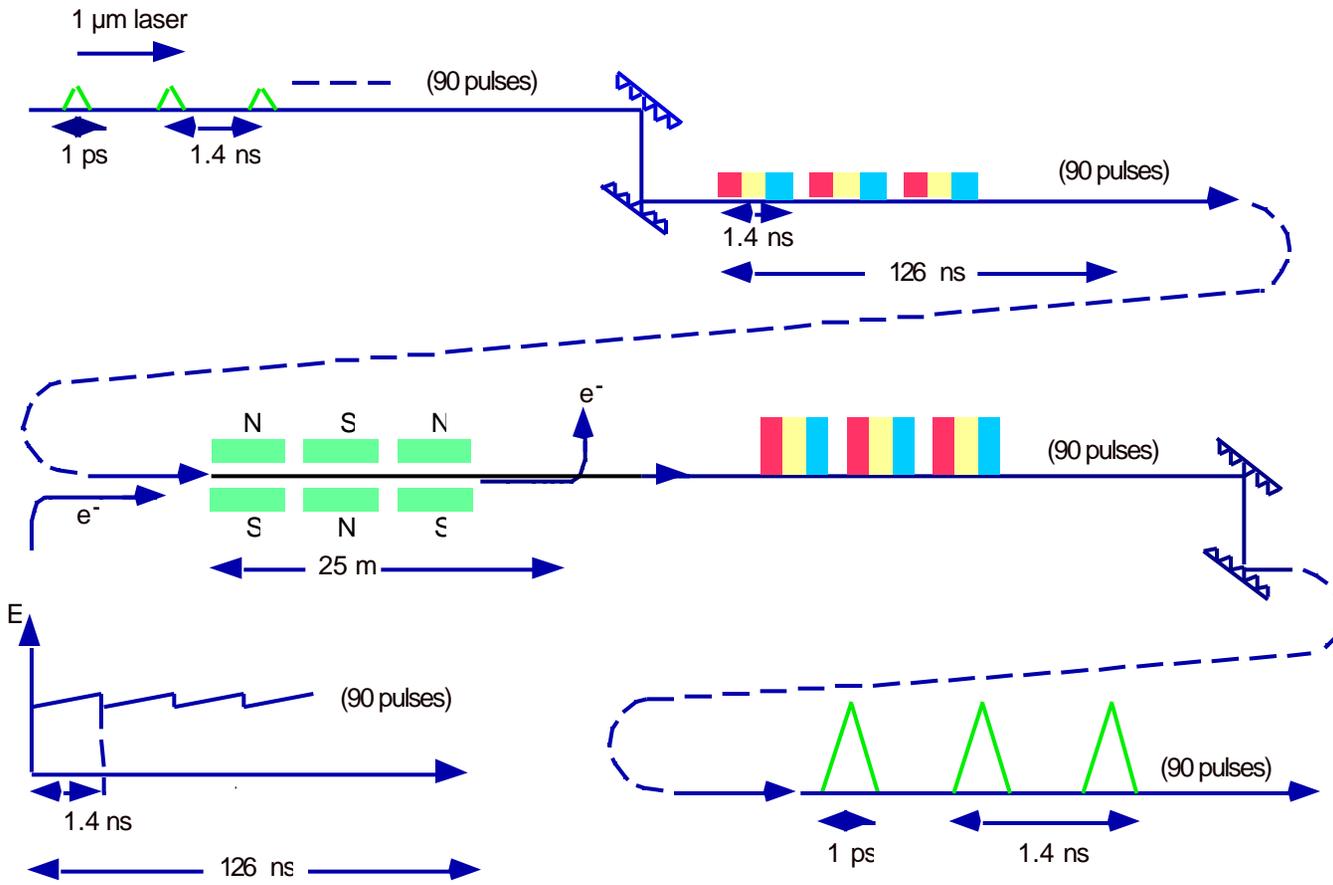
Primary Focus of the Experiment is to Understand :

- Photon statistics and phase space $d \cdot o \cdot f$
- Overlap — "transverse" — of the electron beam and undulator radiation wavefront
- Coherence volume in the transverse plane :

$$x \quad x \quad \sim \quad \lambda$$

- Distortion of radiation wavefront due to amplification, propagation, etc.







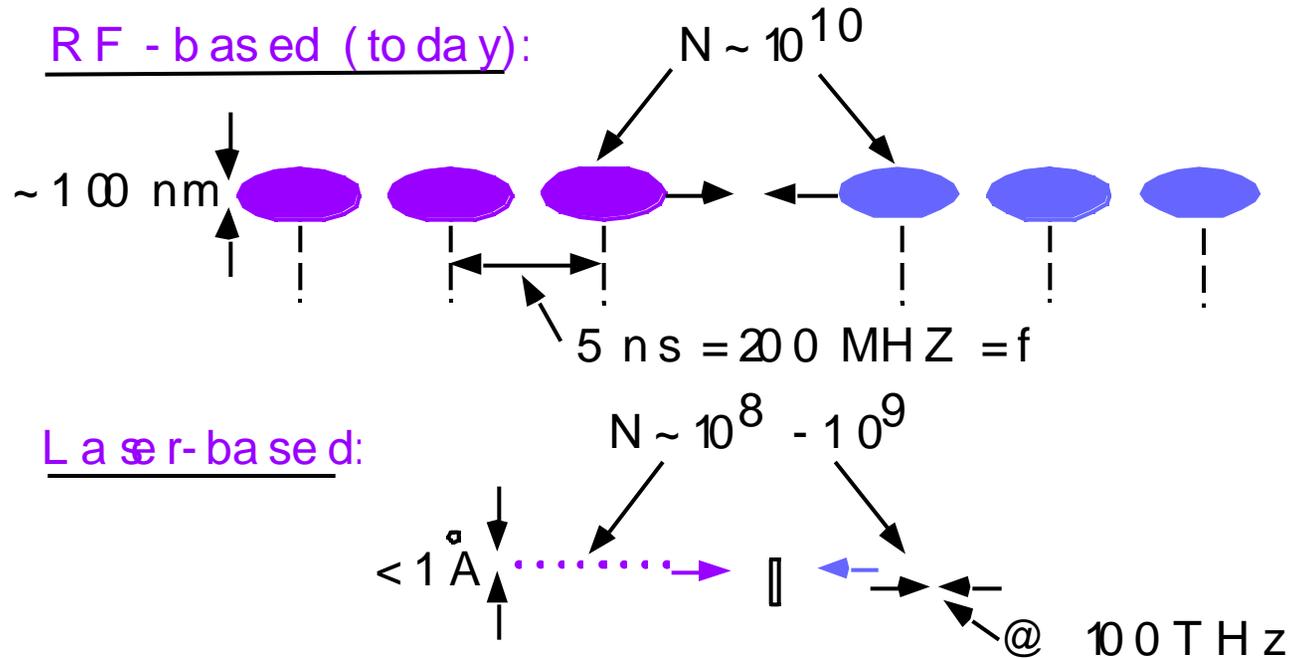
Radiation Sources

Characteristics

- Wavelength coverage
- Spectrum and spectral brilliance
- Coherence
- Pulse length and structure - average power
- Other features, e.g. polarization, etc.



Operation of increasingly smaller Dimensions and Higher Frequencies



Drivers

RF ~ GHz
 SuperRF ~ 100 GHz
 THz
 Lasers

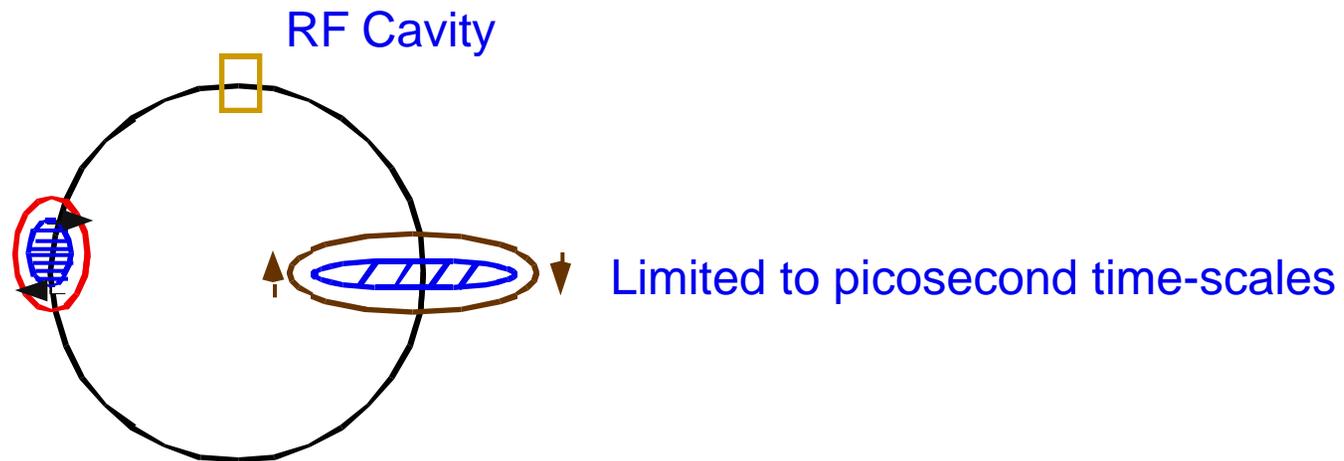
Structures

cms
 mm
 100 μm
 μms in plasmas



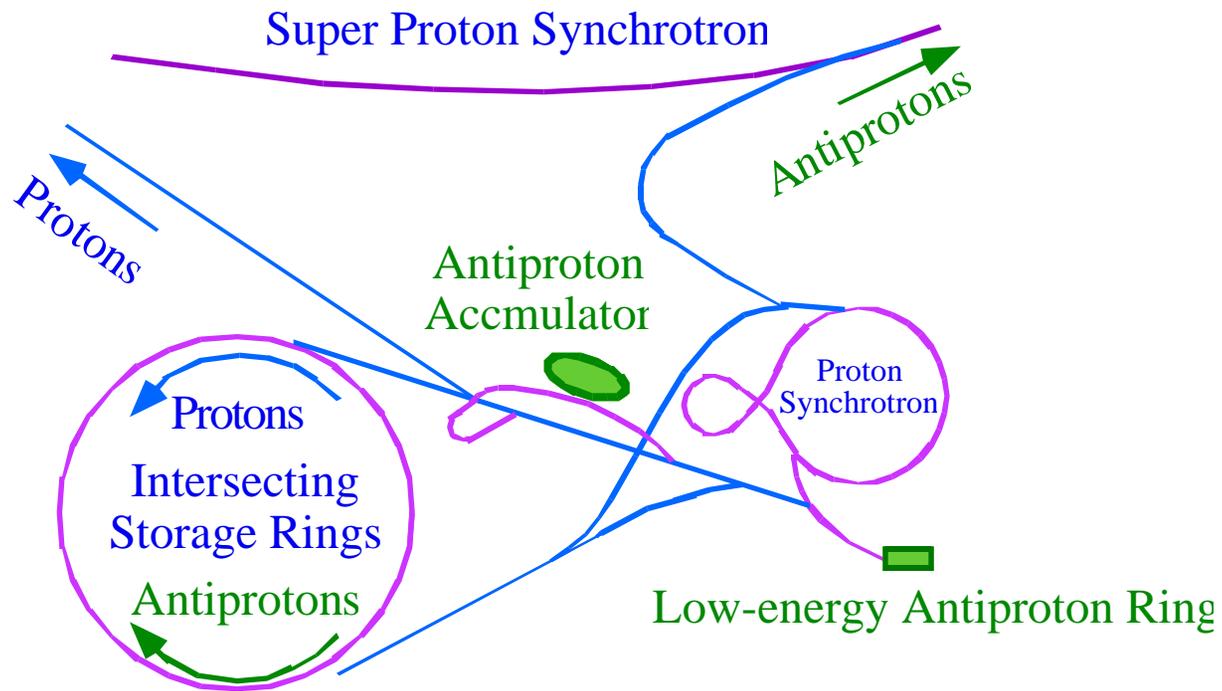
- STORAGE RINGS :

Rapid bunch rotation in a storage ring used as a synchrotron light source.

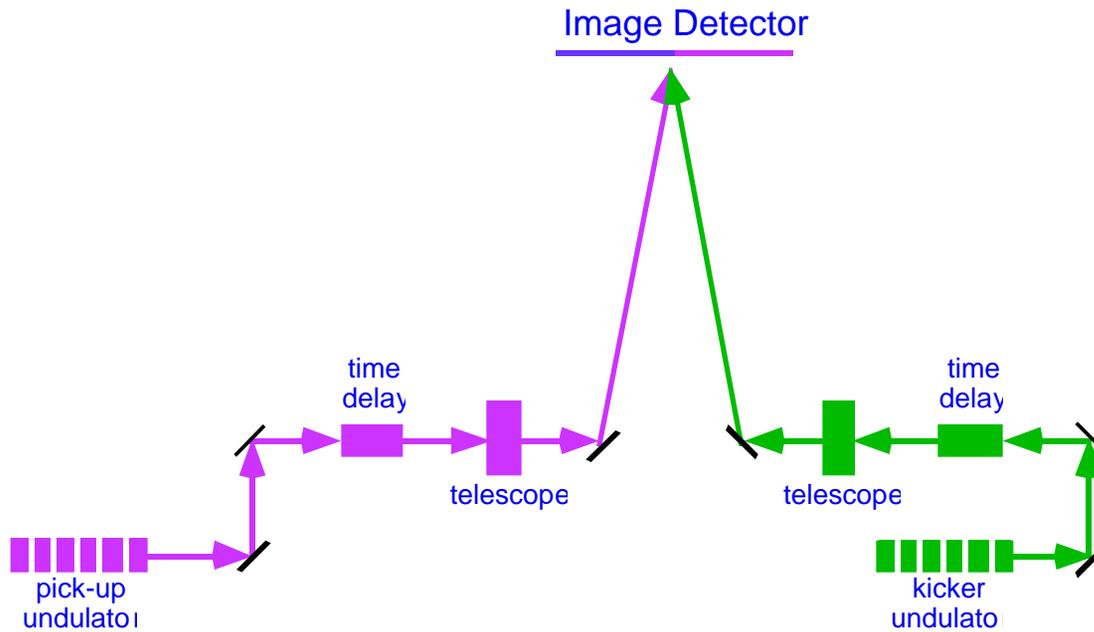




CERN $p\text{-}\bar{p}$ Collider as it looked in 1982



Test of "Non-Mixing" via Fringe Visibility



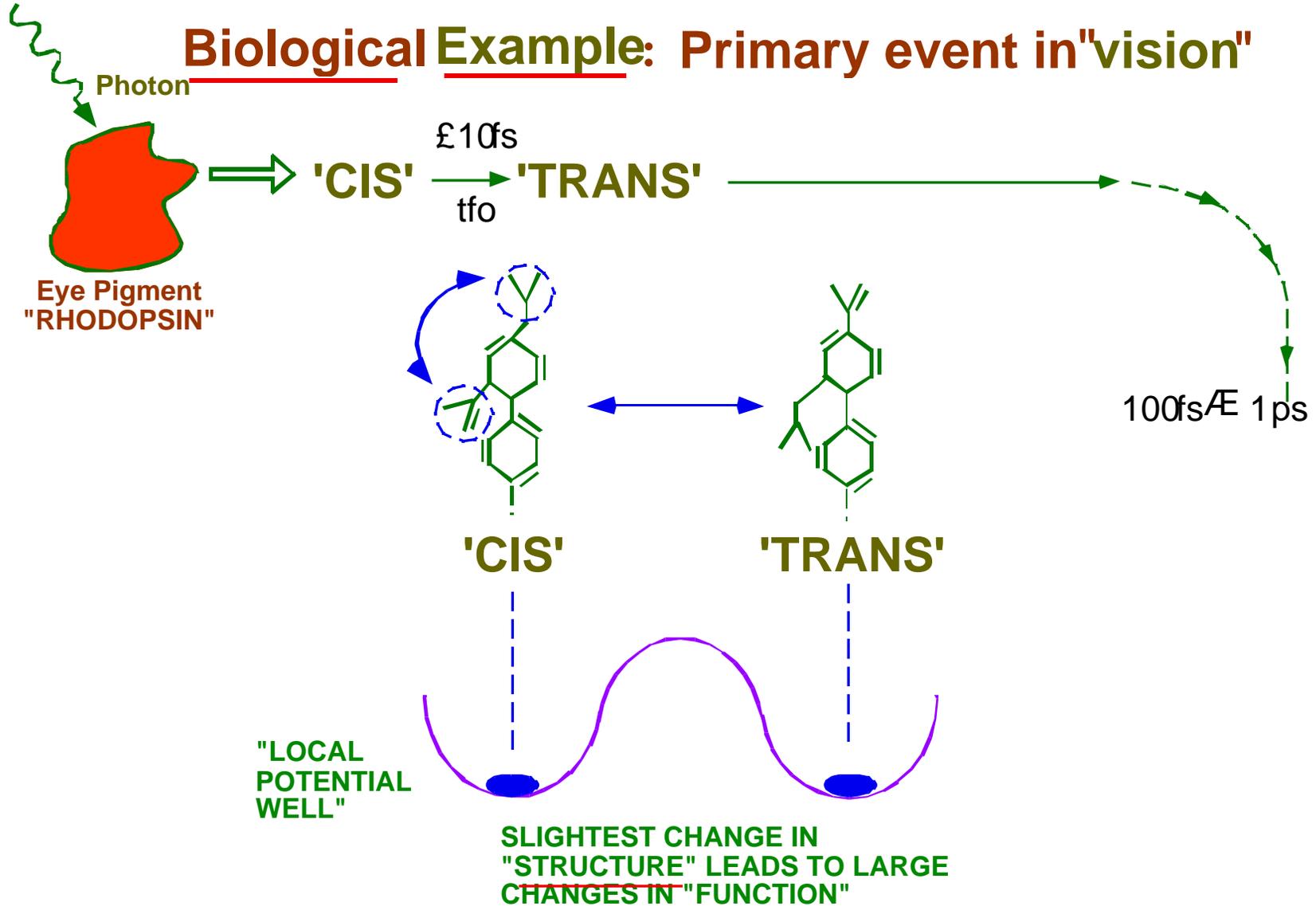
Preservation of fluctuations in the electron beam in the passage between undulators. Visibility of the interference pattern :

$$\text{Visibility} = \exp - \frac{(k \ell)^2 + (k \ell)^2}{2}$$

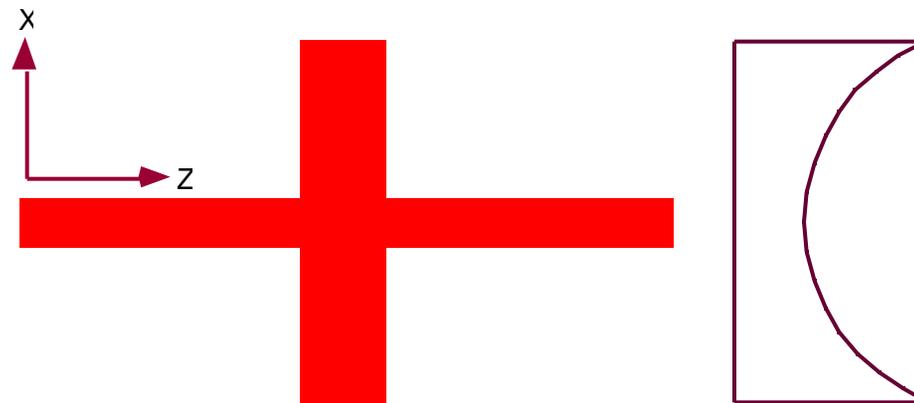


ULTRAFAST COHERENT CHEMICAL REACTIONS

Biological Example: Primary event in "vision"



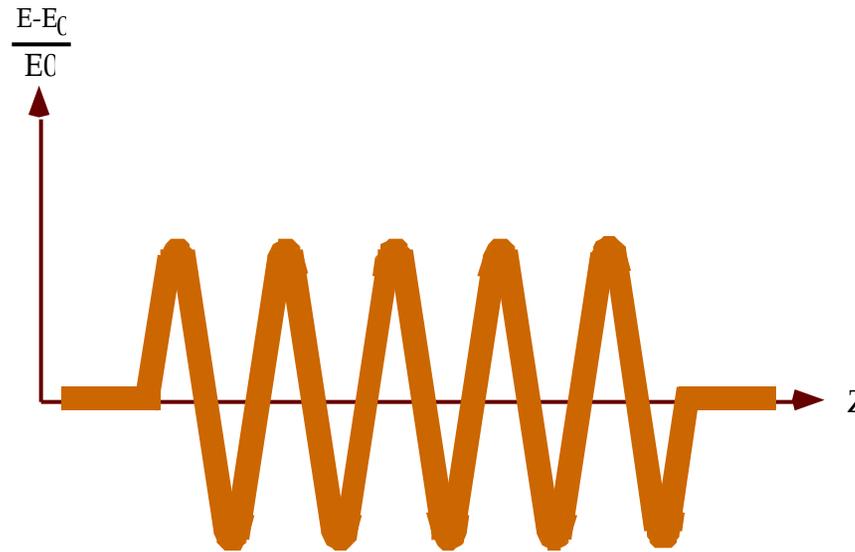
- Electrons (previously energy modulated) will be spatially separated in a dispersive region



- Top view on a fraction of the electron bunch and particle density distribution in the horizontal plane



- Few mJ's in the laser pulse is enough to produce modulation amplitude of $5-10s_e$.



- Longitudinal phase space portrait of a fraction of the electron bunch after interaction with the laser pulse



BERKELEY LAB